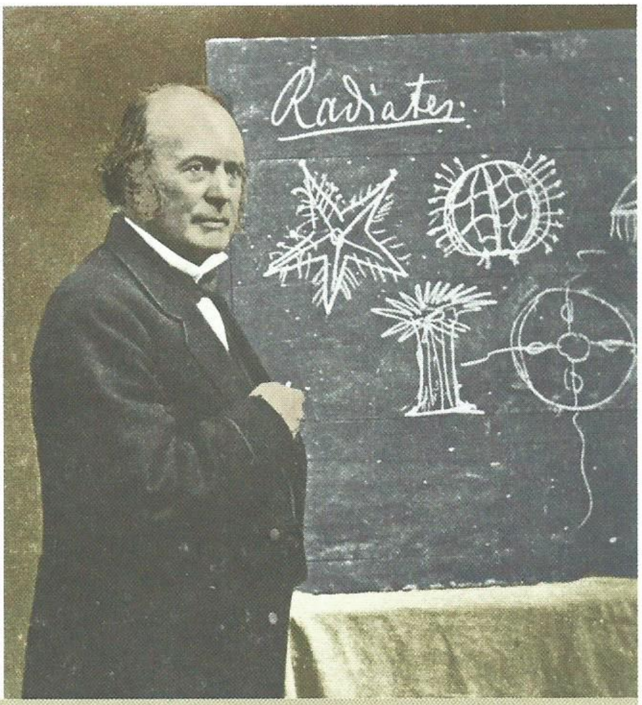
I

ICE AGE. The *Etudes sur les glaciers* by the Swiss botanist and geologist Louis Agassiz (1840) opened the eyes of geologists to the possibility that a great ice age had occurred in the recent geological past. The evidence for the hypothesis was already well known. In northwestern Europe, the location of almost all early geological research, a thick layer of boulder clay covered the bedrock, huge stones (erratics) turned up far from their mother strata, bare rocks showed long, parallel scratches, and the remains of earlier beaches appeared well above existing sea levels. Until Agassiz, though, these manifestations had been put down to a vast flood. Since most naturalists still believed in the relative youth of the earth, they relied on written testimony as much as on field evidence. An ancient flood figured prominently in Greek authors such as Ovid as well as in Genesis. Moreover, from the early nineteenth century, most geologists held that the earth had cooled from an originally hot state, making it difficult to contemplate a past ice age.

Louis Agassiz drew on work by earlier Swiss geologists to reinterpret the phenomena and argue that most of Europe had been covered by an ice sheet. By the early 1860s, even the most reluctant geologists, such as Charles Lyell, had grudgingly come to agree. What caused the ice age, Agassiz never explained. In the nineteenth century, a Scottish autodidact, James Croll, set forth the most satisfactory attempt in his book, *Climate and Time* (1875). He suggested that as the shape of the earth's orbit slowly changed as a result of gravitational interactions with other planets, the variations in ellipticity caused occasional ice ages. One of the consequences of his theory was that glacial conditions in one hemisphere would be opposed by interglacials in the other hemisphere.



Jean Louis Rodolphe Agassiz (1807–1873), Swiss-born American paleontologist, zoologist, and geologist

Scientists soon invoked ice ages to solve other problems. They explained the well-known changes in sea level around the Baltic by the locking up of sea water as ice or by the depression of the crust under the weight of the ice. They suggested that humans had reached North America by crossing from Eurasia on a bridge of ice. They told the story of much of human pre-history as a series of adaptations to life on the southern edge of the Eurasian ice cap.

By the 1920s, using fieldwork by the United States Geological Survey and studies on gravel river terraces by German geologists, scientists had decided that Agassiz's great ice age had in fact consisted of four different stages of advance and retreat. Since these stages occurred in the southern hemisphere as well as in the northern, geologists dropped Croll's theory. Following suggestions that radiation was the decisive cause of glaciation, Milutin Milankovich, a Serbian mathematician, calculated the radiation received in the two hemispheres at various times in the last half million years. At the time, these calculations did not seem to offer the needed support for the four-stage theory.

Following World War II, scientists abandoned the four stage theory as inconsistent with their findings from deep-sea cores. Correlations between the ages of the cores, their paleomag-netism, and their temperature at the time of formation (using oxygen isotopic ratios) revealed a more complicated story that seemed to fit better with information about radiation cycles. As regards the cause of ice ages, though, the verdict is still out.

RACHEL LAUDAN

IMMUNOLOGY as science dates from the 1880s, although inoculation against smallpox goes back many centuries. The history of immunology falls into two periods, before and after World War II. It begins with serology: identification of bacteria, clinical application of vaccines and sera to infectious diseases, and the chemical problem of specificity. After the war, transplantation and grafting rather than infectious disease led immunological work. Unlike other biosciences, immunology was not reductionist: newer work concentrated on the activities of cells rather than on chemistry. The field grew rapidly in the 1960s and 1970s as the new cellular immunology developed; many of those who participated wrote accounts of the period. The historiography of the subject developed in the 1990s and deals with social, scientific, and business history. French writing on the subject has an epistemological twist.

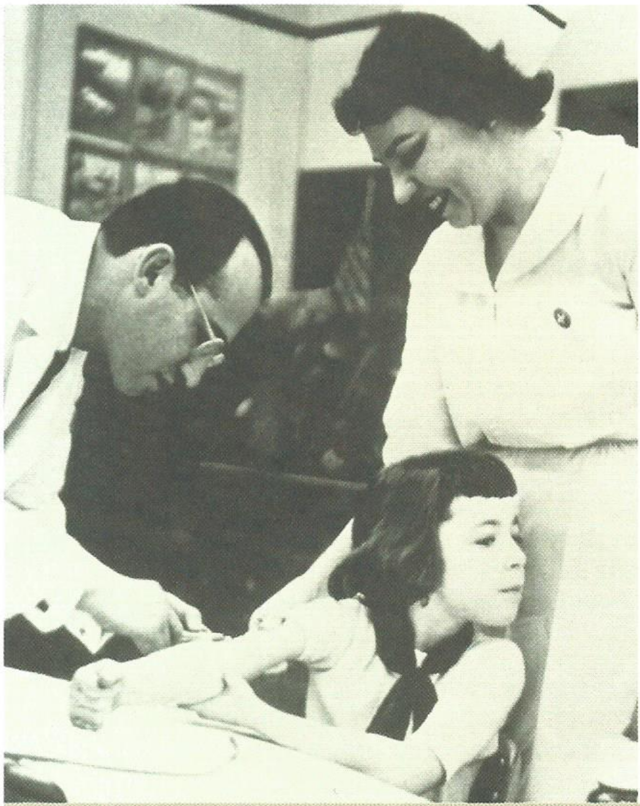
Smallpox inoculation originated in Asia and the Middle East, came west in the 1700s, and may be responsible for the decline in smallpox deaths by about 1790. Vaccinia (cowpox) as inoculum was suggested several times in the late 1700s, most famously by Edward Jenner, a country doctor (though it is unclear if the material he used for vaccination was actually *Vaccinia*). Production was unregulated, and the operation painful and sometimes ineffective; nonetheless health authorities enforced inoculation through such measures as the British Compulsory Vaccination Act of 1853. Compulsion led to worldwide antivaccination movements with strong political and anticolonial overtones.

The Age of Serology, 1890 to 1950

In the 1880s, evidence for germ theory began to mount. Louis Pasteur announced his rabies vaccine and the Russian zoologist Elie Metchnikoff suggested that white blood cells defended the body against invaders. Pasteur liked Metchnikoff's idea and invited him to Paris. But the Franco-Prussian war of 1870 was still being waged on the intellectual front and a rush of publications from Robert Koch and his Berlin colleagues overtook Metchnikoff's work. As bacteriologists, the German scientists were more interested in immune serum, which could be used to identify bacteria, and ignored cells. Animals could be immunized not only with bacteria, but also with bacterial toxins, and immunity transferred passively to another animal via serum. In 1891, antiserum against the toxin of diphtheria proved to be effective in treating the disease. Serum manufacture using horses began at the Institut Pasteur; a global network of serum institutes followed. In Germany, the state guaranteed production and standardization. On the battlefields of World War I, tetanus antitoxin strikingly reduced the incidence of tetanus. At war's end, the victorious Allies through the League of Nations and its Health Organisation set up their own standardization project at the Statens Seruminstitut Copenhagen, bypassing German laboratories, but still using German techniques.

Standardization was central to serology. Paul Ehrlich's standardization in 1894 of diphtheria antitoxin provided a starting point for theory and research. According to his side-chain theory, cells had receptors (the side-chains) that normally functioned to capture nutrients. The receptors could be blocked by toxin, which caused the cell to repair itself by producing an excess of new side-chains, which were shed into the serum and formed serum antitoxin. Toxin and antitoxin bound irreversibly on contact. Specificity was absolute. Ehrlich called this a pluralistic view; receptors for every possible antigen were already present in the normal animal. His critics objected that the theory required far too many specific substances.

The alternative, propounded by Karl Land-steiner of Vienna, gained currency after 1900. Specificity became approximate, a matter of the closeness of fit, determined by the charge outline of antigens. The antigen-antibody reaction became reversible as in colloid chemistry. On this view, antibody might be formed by assembling protein molecules on antigen as template, as the Prague chemist Felix Haurowitz suggested in 1928; unlike Ehrlich's theory, Landsteiner's required no preformed antibody. But Ehrlich's vocabulary and his cartoon-like pictures of the union of antigen and antibody outlived his chemistry. A century later, we still speak of receptors. In the mid-1920s, Swedish chemists began differentiating serum proteins, first by molecular size in the ultracentrifuge, then by charge and then by both together. Antibody activity was found to lie in the globulin fraction of the serum protein. This work led to Rodney Porter's elucidation of the four-chain structure of antibody globulin (1962), the definition of a family of different immunoglobulins each with a different immunological function, and to the sequencing of the amino acids making up the chains.


American microbiologist Jonas Salk (1914–1995) runs tests on his vaccine against polio.

Cellular Immunology, 1950s to 1980s

Antibiotics came in with World War II and although new vaccines still appeared, notably Jonas Salk's polio vaccine (along with antivac-cinationism), serological treatment of disease declined. Thinking became more biological, dealing with reactions in animals and cells rather than serological chemistry. The key problem was graft rejection, important in wartime along with blood transfusion. Discussion centered on tolerance: Peter B. Medawar in London, arguing on the model of the blood groups, suggested that graft intolerance was immunological, while Frank Macfarlane Burnet in Australia taught that tolerance of self developed in fetal life. Various theories appeared bringing antibody-producing cells to the fore: selection theories of antibody production reappeared. Burnet's fruitful clonal selection theory proposed that immunocompetent cells carried a range of natural antibodies as receptors. Antigen triggered multiplication of a clone of cells, and each clone produced one specific antibody. Clones that recognized foreign (that is, nonidiopathic) material survived the fetal period, self-clones being eliminated. This view overtook the template theory about 1967. Burnet linked immunology to modern biology through Darwinian selection and the population genetics of clones, and to current thinking on protein genetics.

An avalanche of new work focused on populations of lymphocytes—then cells with no known function, now seen as mediating the immune response, including immune recognition and memory. Immunological experimentation turned to the reactions of animals, usually inbred mice. Old cells-versus-serum controversies were resolved as it appeared T lymphocytes, developing in the neonatal thymus, mediate cellular immunity and interact with B lymphocytes from the bone marrow, producers of serum antibody; the cells cooperate via messenger molecules named lymphokines. At this point, Anne-Marie Moulin suggests, researchers began to recognize an "immune system." Clinical applications of cellular immunology included autoimmunity, hypersensitivity, and transplantation surgery. Pharmaceutical companies patented immunosuppressants and, later, perfectly specific monoclonal antibodies originally derived from cultured myeloma, a cancer of lymphocytes.

In the 1970s, with increased funding especially in the United States, the profession expanded: journals proliferated, congresses national and international were initiated, symposia and courses organized.

Acquired immune deficiency syndrome (AIDS) appeared in 1982; human immunodeficiency virus (HIV), isolated in 1984, was found to affect a particular subpopulation of lymphocytes, the T4 cells, key to the immune response. T4 cells became part of popular discourse and historians too became interested in immunology.

Pauline M. H. Mazumdar

IMPONDERABLES. Around 1800 physical science enjoyed a fleeting unification under a scheme that developed from study of the phenomena of heat and electricity. The discovery of the conduction of electricity down damp threads by Stephen Gray in 1729 prompted the assimilation of the agent of electrical attraction to water running through a pipe, an analogy strengthened by Benjamin Franklin's comparison (1751) of the machines used for generating electricity (globes or cylinders of glass spun against the hand) to pumps, and Leyden jars (condensers) to reservoirs. For those who accepted Robert Symmer's version of Franklin's theory (1759), which made negative charge as real as positive, electricity was served by two fluids, which, since ordinary bodies appeared to weigh no more when electrified than when not, were taken to be imponderable.

In order to explain the most evident electrical phenomena, natural philosophers ascribed repulsive and attractive forces to the droplets of the electrical fluids: repulsive between droplets of the same fluid, attractive between those of different fluids and between the fluid(s) and ordinary matter. To account for the differences in the degree of electrification or tension exhibited by insulated conductors of different shapes and sizes electrified in the same way by the same machine, philosophers ascribed a pressure to the electrical fluid(s) and specific electrical capacities to the conductors. Johan Carl Wilcke and Alessandro Volta developed these concepts in the 1770s.

Most chemists and natural philosophers of the eighteenth century traced the action of heat to a special substance, which, like electricity, was understood to be an expansive fluid because of its spontaneous "flow" from hot to cold bodies. Also like electricity, its parts were taken to be self-repellent in order to explain the expansion of bodies when heated. Within the Newtonian philosophy the self-repellency of heat arose from a repulsive force acting between the particles of the heat fluid. With the discoveries of latent and specific heats by Wilcke and Joseph Black in the 1770s and 1780s, the parallels between the heat fluid and the agent of electricity broadened: latency could be regarded as a bonding between heat and matter; specificity indicated an analogy between temperature and heat capacity, on the one hand, and tension and electrical capacity, on the other.

The standard representations of magnetism and visible light easily fit the imponderable model. By analogy to electricity, magnetism came to be regarded as a distance force arising from magnetic fluid(s) whose particles obeyed the same rules of attraction and repulsion that regulated the traffic of the electrical fluids. The main distinction—that nothing comparable to conductors of electricity existed for magnetism—was regarded as a question of degree not kind. The magnetic fluid(s) stayed in magnetic substances as electrical fluid(s) did in strong insulators. Franz Aepinus worked out these parallels in detail in 1759. As for light, its particulate nature was assured by the widely held optical theories of Isaac Newton, which endowed light particles with short-range forces by which they interacted with matter to produce the phenomena of reflection, refraction, and inflection (diffraction). The capstone of the arch of imponderables was the discovery by William Herschel in 1800 of radiant heat beyond the red end of the visible spectrum. Infrared light connected heat and ordinary light and, via the analogies between heat and electricity, light with magnetism. More speculative philosophers added fire, flame, phlogiston, and what-not to the generally accepted five (or seven) imponderables.

The scheme, which functioned as a standard model for physical science around 1800, had two important assets. For one, it immediately explained the existence of the phenomena it covered by the mere presence of the relevant agent. For another, it lent itself to the fashion of science of the time, quantification. In 1785, Charles Augustin Coulomb established to the satisfaction of the members of the Paris Académie des Sciences (and few others) that the interfluid forces in electricity and magnetism declined, as did the force of gravity, with the square of the distance between interacting elements. Pierre-Simon Laplace and his school pursued the program of quantifying the distance forces that are supposed to act between elements of the heat fluid (which they called caloric) and between light particles and matter. Laplace and Jean-Baptiste Biot managed to give detailed accounts of refraction, both single and double; polarization; and other optical phenomena in these terms. By taking literally the concept of heat as a conserved fluid, Laplace created a brilliant theory of adiabatic processes that resolved the longstanding and scandalous discrepancy between theoretical treatments and measurements of the speed of sound in air. Although it did not appeal to the notion of distance forces, the adiabatic theory encouraged belief in the existence of caloric.

A serious fault with the scheme of imponderables, apart from its multiplication of weightless fluids at a time when chemistry was learning to live strictly by the balance, was the ontological independence of the several fluids. The unification the scheme brought rested on parallel treatment of diverse phenomena, not on connections among their agents. This weakness was partially overcome by the linking of electricity and magnetism beginning with the discovery of the action of a current-carrying wire on a magnet by Hans Christian Oersted in 1819. But the replacement of the particulate by the undulatory theory of light in the early nineteenth century, and the annihilation of caloric by the kinetic theory of heat in its middle decades, destroyed the old standard model. A new synthesis seemed imminent and immanent in James Clerk Maxwell's unification of electricity, magnetism, light, and radiant heat, and the program pursued around 1900 to reduce ponderable matter to electromagnetism. That program failed, leaving the electron, the electric current, and the flow of heat as residues and reminders of the first standard model in physics.

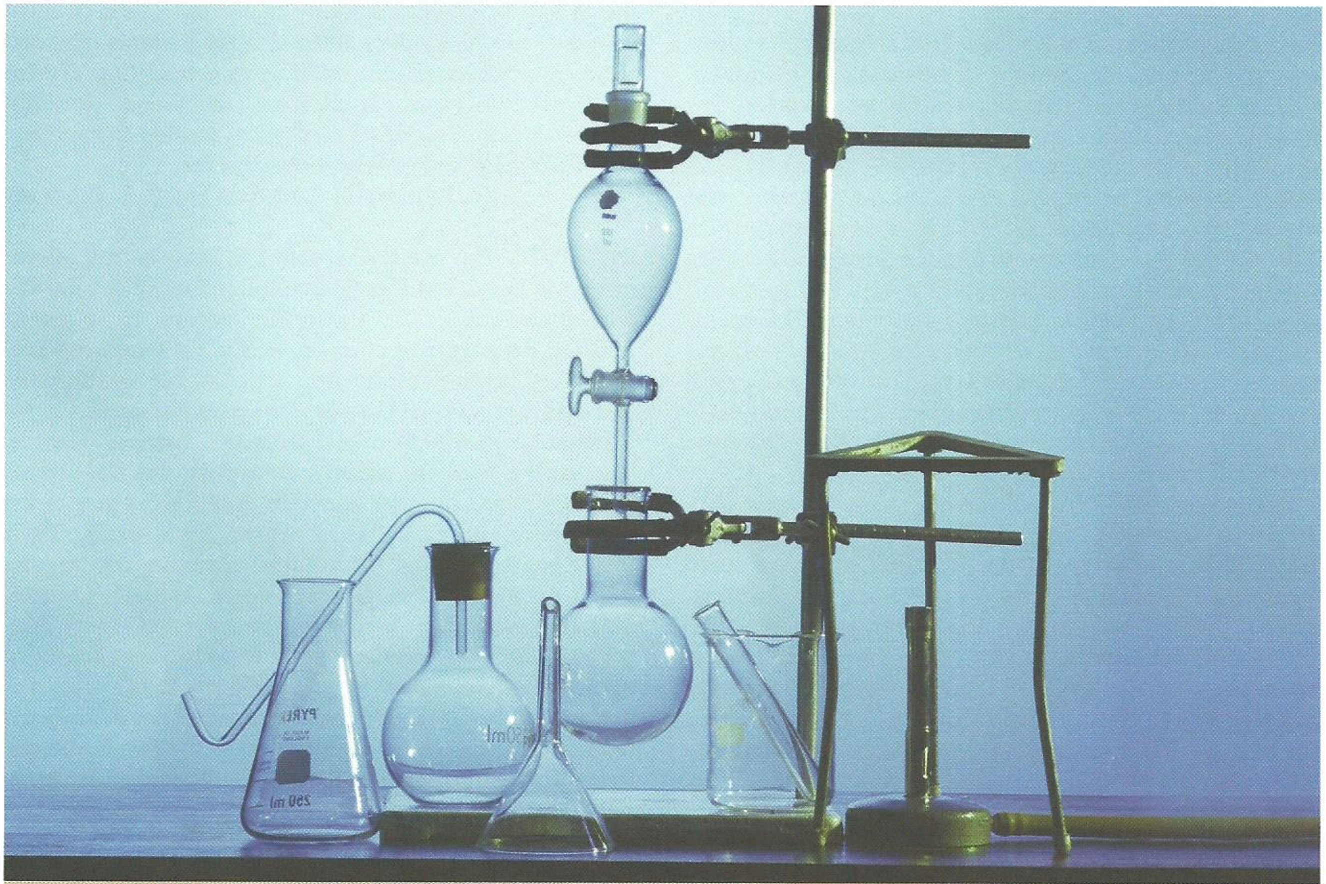
J. L. HEILBRON

INORGANIC CHEMISTRY. Traditionally, chemical substances were classified on the basis of their origins, the most general distinctions being between the mineral kingdom and the animal or vegetable kingdoms. After the demonstration in 1828 that urea, a compound produced by living things, could be synthesized from inorganic chemicals, the discipline of organic chemistry developed as a distinct area of study—the chemistry of compounds of carbon and the elements with which it readily combines (hydrogen, oxygen, nitrogen). Inorganic chemistry then became the chemistry of compounds of all the elements other than carbon. This early distinction based on origin accounts for the peculiarity that a few carbon compounds—such as the oxides, carbonates, and cyanides—are still generally regarded as inorganic. As a recognized area of study, inorganic chemistry dates from the nineteenth century, but as a practical interest in substances from inanimate sources, it is rooted in alchemy and it stretches back centuries to mining, metallurgy, medicine, dyeing, glassmaking, and gunpowder production.

Among the numerous problems facing nineteenth-century chemists, many revolved around the lack of agreement over standards, such as chemical notation and an atomic-weight scale. Two chemistries seemed to exist, organic and inorganic, each with its own set of atomic weights. At the International Chemical Congress at Karlsruhe, Germany, in 1860, the Italian chemist Stanislao Cannizzaro circulated a short paper on the problems associated with atomic weights and ways of resolving them. During the next decade chemists succeeded in clearly distinguishing between atoms and molecules, reforming and standardizing atomic weights, and reuniting the two chemistries with a single set of conventions.

While catalyzing reform, Cannizzaro's paper also had a profound effect on the thinking of many chemists, including Dmitrii Mendeleev and Lothar Meyer, both of whom organized the elements on the basis of increasing atomic weight (Mendeleev in 1869 and Meyer in 1870). The modern periodic table, the eventual outcome of this organization, is more closely associated with Mendeleev, who was by far the bolder of the two. He not only organized the elements into a table based on his periodic law, but also predicted the existence of several elements that were unknown at that time, as well as their properties. These represent one of the first instances of successful prediction in chemistry. Mendeleev's table assumed its modern form in 1914 when the English physicist Henry G. J. Moseley organized the elements on the basis of increasing charge in the atomic nucleus, i.e., increasing number of protons.

In 1858, the German chemist August Kekulé advanced his theory that the atoms in molecules are arranged in specific ways relative to one another. These structural formulas, along with the idea that the valence or "combining power" of an atom is constant, worked very well for organic compounds and fueled the dramatic growth in this area of chemistry after 1860. Kekulé tried to extend these ideas to inorganic compounds, but they failed even in simple cases. More complicated molecules—like those of the coordination compounds first synthesized during the nineteenth century—were particularly problematic.



The enduring apparatus of inorganic chemistry: clamp and trivet stands, Bunsen burner, various flasks including one for titration, and a test tube

While an assistant to Robert Bunsen in Marburg, Germany, Frederick Augustus Genth synthesized several ammonia-cobalt compounds in 1847. He published this work in 1851 after emigrating to the United States. The following year the American chemist Wolcott Gibbs also began investigating these compounds, and in 1856 he and Genth jointly described the synthesis and analysis of thirty-five ammonia-cobalt compounds. Their report of the properties and striking colors of these unusual compounds presented a challenge to theorists.

In 1869, the Swedish chemist Christian Wilhelm Blomstrand made the first attempt to describe the structures of the compounds synthesized by Genth and Gibbs. Making use of the variable valence of nitrogen, he proposed a chain theory, which the Danish chemist Sophus Jørgensen subsequently adopted and modified. This model linked ammonia molecules (NH_3) in an ammonia-cobalt complex together in a chain like the CH_2 groups in an organic hydrocarbon compound. More importantly, Jørgensen prepared and examined many new complex compounds, including some with chromium, rhodium, and platinum, as well as cobalt. He also determined many of their physical properties. The vast amount of experimental data collected by Jørgensen, Gibbs, and Genth was essential to the subsequent development of the revolutionary coordination theory.

The theory, a foundation-pillar of inorganic chemistry proposed by Alfred Werner, represented a new way of describing inorganic compounds and was not merely a modification of organic structural theory. Werner obtained his doctorate from the University of Zurich in 1890 with a dissertation on the spatial arrangement of atoms in molecules containing nitrogen. In 1893, the year he began teaching at the University of Zurich, he published the first of his papers on his theory of variable valence. He described molecular inorganic compounds as having a central (metal) atom surrounded by a definite number of other atoms, molecules, ions, or radicals in a three-dimensional arrangement. The number of such groups around the central atom was termed the coordination number. The ammonia-cobalt compounds have a coordination number of six, the six ammonia molecules being arranged at the vertices of an octahedron (8 faces defined by 6 vertices—two square pyramids sharing a common square base) centered at the cobalt. Werner's coordination theory provided a tool for understanding not only inorganic compounds and reactions, but also many organic and biochemical reactions, such as those involving Grignard reagents in which a central magnesium ion is coordinated with both halide ions and organic groups. Werner received the Nobel Prize in 1913.

Since many chemists regarded Werner's monumental work as having completed inorganic chemistry, the subject generated little interest during the early part of the twentieth century. The American Chemical Society further marginalized the field by making it an area within physical chemistry. Not until the Manhattan Project in the early 1940s and the need to separate uranium isotopes did the field of inorganic chemistry began to flourish again. A group of chemists organized a separate Division of Inorganic Chemistry within the American Chemical Society and began the journal *Inorganic Chemistry*.

The 1950s mark the reemergence of inorganic chemistry. Although the first organometallic compound was synthesized in 1827, chemists could not devise an adequate description of its structure and bonding until the early 1950s when they prepared and studied many other such compounds. The structure of one of these novel molecules, ferrocene, was elucidated by two Harvard chemists and subsequent Nobel laureates, Robert Woodward and Geoffrey Wilkinson. The ferrocene "sandwich" has an iron(II) ion as the bonding center between two parallel, aromatic, five-member carbon rings. The development of quantum mechanics and significantly improved understanding of atomic structure led to new bonding theories that can interpret these novel structures satisfactorily.

Another pivotal figure in inorganic chemistry of the second half of the twentieth century is F. Albert Cotton, a former student of Wilkinson's. His textbook, *Advanced Inorganic Chemistry,* written with Wilkinson and currently in its sixth edition (1999), has trained several generations of chemists since its first edition in 1962. Cotton's 1963 textbook, *Chemical Applications of Group Theory,* which appeared in its third edition in 1994, has provided chemists with an extremely powerful tool for understanding, explaining, and modeling the structure and reactivity of inorganic compounds.

The resurgent inorganic chemistry originating in Werner's "completed masterpiece" is an essential component of materials science, an interdisciplinary field that blends chemistry and engineering. Thin films, industrial diamonds, ceramics, superconductors, semiconductors (both traditional and organic/organometallic), LEDs (light-emitting diodes), and lasers are a few of the materials and devices that will continue to be improved through advances in inorganic chemistry. Current trends that should have significant results in the twenty-first century include greater theoretical understanding of the formation of ceramics, leading to improved materials for engineering; synthesis, development, and manufacture of organometallic LEDs; synthesis of diamond and other commercially important films; detailed computer models of every element in the periodic table and three-dimensional visualization tools accelerating growth in all aspects of inorganic chemistry; and a more powerful understanding of quantum mechanics, leading to improved communication and computational devices.

RICHARD E. RICE AND FRANK A. PALOCSAY

INSTITUTE. The university-based institute was the instrument and symbol of Germany's dominance of natural science at the end of the nineteenth century. In its spatial isolation from the rest of its university, the institute represented and enforced the division of the sciences by discipline and of the professoriate by research accomplishment.

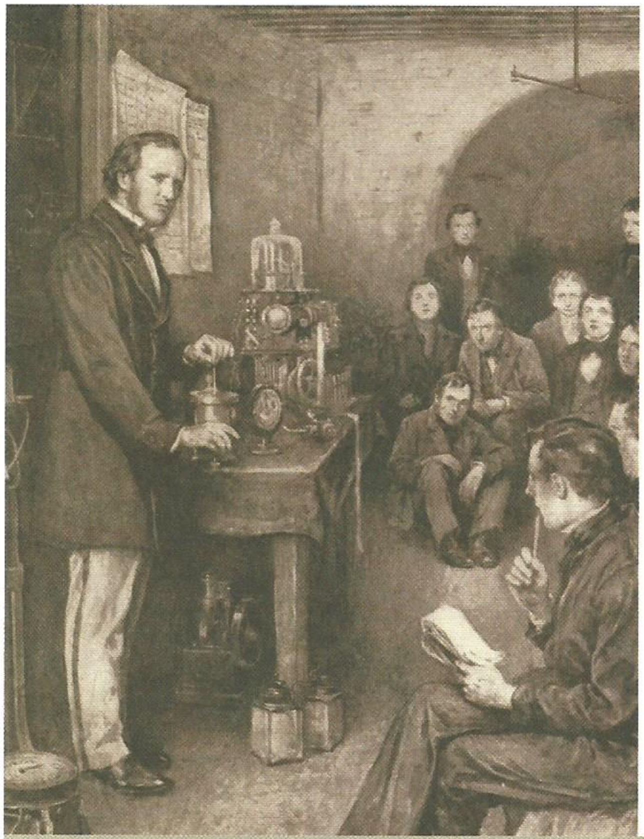
Institutes evolved from two university practices. The earliest, dating from the eighteenth century, was the cabinet for instruments or other materials used for demonstration in teaching and to a limited degree, for research. Their maintenance required workrooms; their use for instructional demonstrations, lecture rooms. Initially privately owned, cabinets were placed on the university (state) budget by 1850. The evolution of cabinet to institute depended upon the establishment of university laboratories and the inauguration of the professorial research ethos in the early nineteenth century. Institutes were thus the principal venue through which the manual practices associated with experimental research became a regular part of university instruction in the sciences. An early example is Justus von Liebig's chemistry laboratory at Giessen, founded in 1826.

The second university practice that gave rise to institutes dates from the early nineteenth century. The emphasis German elites placed on *Bildung* (the formation of mind and character)—based in study of ancient languages, philosophy, history, and later theoretical natural science and taken as the key to advancement at higher levels of government service—was a central impetus in the development of new methods of instruction based on learning the principles of research. To prepare secondary teachers capable of imparting proper *Bildung*, professors of philology created special seminars in which students were systematically taught disciplinary knowledge and research methods that could in principle lead to the production of original research. This model entered the natural sciences in 1825 in the Bonn seminar for the natural sciences, followed in 1835–1836 by the establishment of the Königsberg seminar for physics and mathematics, directed by Carl Gustav Jacobi, a classicist turned mathematician, and the mineralogist turned physicist Franz Ernst Neumann. Like the university cabinet, the seminar required a dedicated budget, director, and space. Before 1850, when laboratories began to appear alongside cabinets, they also were found associated with seminars in either the natural sciences or physics and mathematics combined. Managing and maintaining the cabinet, laboratory, and seminar required increasingly greater financial resources and support services, adding to the administrative complexity of these units. As the professorial research ethos took hold and instructional techniques for transmitting it to students were developed, the nature of instruction became ever more complex.

In the second half of the nineteenth century, the institute emerged as the principal site in the university of original research, both professorial and student. The institute by then was an amalgamation of physical space, financial resources, material supplies and equipment, student clientele, support staff, and professorial leadership. The longstanding German tradition of having a single full professor (*Ordinarius*) per discipline stamped the organizational structure of the institute as one run by a director who had near total control over all persons in the institute's sphere, including assistant and associate professors (*Privatdozenten* and *Ausserordinarien*).

The success of the instructional mission of institutes beyond the production of scientific practitioners (where success was uneven) can be measured by the demographics of their student clientele. Chemical institutes, like Liebig's, included students who wished to become physicians, pharmacists, agriculturalists, and future secondary teachers. Similarly and simultaneously physics institutes furthered the careers of physicians and secondary teachers. Seminars in all the natural sciences, which generally had poorer resources than full-fledged institutes, catered in addition to geographers, technicians, astronomers, businessmen, and civil servants. Students interested in technology and engineering found places in institutes in the Technical High Schools (Technische Hochschulen), which began to multiply after 1870. Institutes thus spread through the educated male elite in Germany an outlook not only familiar with the techniques of research, but one highly appreciative of its social and cultural values as well.

The institute phenomenon eventually took over the entire university system in Germany. Resources devoted to teacher (and research) training grew faster than resources devoted exclusively to service teaching. For example, in 1873 the University of Leipzig replaced an old physics cabinet, built in 1835, with an institute four times as large. This, in turn, was replaced by one three times larger still in 1904. Laboratory facilities occupied 12 percent of the cabinet, 46 percent of the first institute (1873), and 60 percent of the second—if the thirteen rooms and veranda of its baronial quarters are deducted, 75 percent. Most of the increase came in small rooms for individual research rather than in teaching laboratories and lecture halls.



A physics institute, Scottish style, in the later nineteenth century: William Thomson (1824–1907), later Lord Kelvin, lecturing in his basement laboratory at the University of Glasgow.

The system was in principle continuously renewed by the "call"—the invitation of a professor in one state to take over an institute in another. The invitee would negotiate with both, for equipment and space as well as salary. A man in demand might leave a string of new buildings in his wake. Hermann von Helmholtz received a new institute of physiology as a dowry when he moved from Bonn to Heidelberg in 1858, and a new physics institute when he moved on to Berlin in 1871.

The institute spread throughout Europe, including Britain, and, with an important exception, the United States. Although American university departments provided disciplinary separation, teaching facilities, and, in time, a research ethic, their more democratic organization thwarted any pretensions of their chairs to papal authority and perquisites, as was the custom in Germany. The long-term historical consequences of the fluidly democratic structure of the department versus the rigidly hierarchical structure of the institute were crucial for the future development of the scientific community in both countries. Whereas American universities have been receptive to interdisciplinary cooperation, German universities have been less so due to the persistence of the rigid administrative practices of the institute. Consequently at the end of the twentieth century, Germany's educational ministers favored interdisciplinarity by encouraging innovation outside the outmoded institute structure and by offering pathways for career advancement for younger scholars that did not rest on permanent appointments in institutes.

By the beginning of the twentieth century competition among the European nations in natural science and its applications prompted the formation of institutes with few if any teaching functions. Among them, the Carnegie Institution of Washington (founded in 1902 with a gift larger than Harvard's endowment), the research departments of the national bureaus of science, and the Nobel institutes for physics and chemistry are prominent international examples, alongside the many institutes of the Kaiser Wilhelm Gesellschaft and the Soviet Academy of Sciences.

KATHRYN OLESKO

INSTRUMENTS AND INSTRUMENT MAKING. Although the concept of a scientific instrument may seem clear, the historian is bound to find it problematic, not least because the term did not come into common use until the second half of the nineteenth century. The present usage, in its application to the past, comes partly from a projection of current scientific practice onto earlier activities and partly from choices made by collectors, curators, and dealers as they constructed a specialist interest in material culture that would guide their activities in museums and salesrooms.

An important function of contemporary scientific instruments is to investigate the natural world, to discover new truths about nature. But until the beginning of the seventeenth century instruments had no such role. In the terminology of the time, some "mathematical instruments" played an integral part in certain mathematical arts or sciences, but had no place in the science that dealt with causes and explanations in the material world, natural philosophy. Practitioners used these to solve problems and produce practical results, such as casting a horoscope, telling the time, finding the latitude, or drawing a map.

Astronomy provides the earliest record of the use of mathematical instruments and through astronomy many of the technical characteristics of mathematical instruments developed. This precedence might be seen as the outcome of a Platonic belief in a geometrical cosmos. But an alternative view is just as plausible. The regulation of time and calendar by the changing appearance of the sky required measurement and invited instrumentation; a Platonic concept of geometrical astronomy may have been a theoretical formulation of an existing operational practice in observing the heavens.

Astronomical instruments fixed in observatories were generally made by bringing together local resources such as woodwork, metalwork, and masonry, whereas personal portable instruments like astrolabes and sundials came from mathematical instrument makers, and specialist workshops in recognized centers of production. One of the earliest makers on whom we have much biographical information was Jean Fusoris, university educated and a church canon, who set up a workshop in Paris and produced astrolabes and clocks in the early fifteenth century.

Other early makers or founders of workshops were leading mathematicians and astronomers. Johannes Regiomontanus established a workshop in Nuremberg in the 1470s; several surviving instruments are attributed to him. Scholarly mathematicians from the sixteenth century with a strong commitment to the development of instrumentation include Peter Apian in Ingolstadt and Gemma Reines (called Frisius) in Louvain. Gemma worked in association first with Gerardus Mercator and later with his nephew Gualterus Arsenius to produce a great many instruments and a variety of new designs. An international trade developed. The Louvain workshop benefited from an understanding with Christophe Plantin whose printing house in Antwerp was used for their ordering and distribution. This arrangement represented a wider association between instrument production and other mathematical commerce, such as mapmaking and book publishing.

The sixteenth century saw a remarkable development in instrumentation as part of a general flourishing of practical mathematics. The development of navigation and commerce and changes in the conduct of warfare inspired new ways of harnessing geometry to more effective action. This activity tended to take place at court or in the city rather than in the university. Mathematics occupied an inferior position in the university hierarchy to medicine, law, and natural philosophy, but at court it could be used as a tool for political and territorial advance, and instruments were used for persuasion as well as action. The appearance of many surviving instruments from this period indicate that their role was partly rhetorical.

Among many new designs from the sixteenth century were different types of sundials, quadrants, and nocturnals for finding the time, universal astrolabes, theodolites, and other surveying instruments, the cross-staff and back-staff for astronomical navigation, and the sector for a wide range of calculations. The publication of many books on instrumentation and the spread of centers of production, notably to Florence, Venice, Nuremburg, Augsburg, Ingolstadt, Louvain, Paris, Antwerp, London, and Prague, accompanied and supported the development in the range of designs.

Because these mathematical instruments did not engage with natural philosophy, they did not have to respect the received account of the natural world. Terrestrial globes rotated on polar axes in advance of the publication of the Copernican theory simply for convenience. Different projections of the celestial sphere could be used on the two sides of a single astrolabe according to their intended applications, a freedom that reflected the variety of projections used in contemporary cartography. In both fields, convenience and efficiency were the criteria of success, not fidelity to nature. At the same time, the status enjoyed by practical mathematicians in nonacademic contexts for work, and their freedom from the disciplinary restrictions of the university, gave them a relative confidence and autonomy that would eventually facilitate the application of their practices to the reform of a demoralized natural philosophy.

The application of instruments to discovering the truths of nature began in the late sixteenth and early seventeenth centuries, most significantly in the use of the telescope in astronomy. Instrumentation had always been part of astronomical practice, of course, but it had been applied to mathematical astronomy, not the natural philosophy of the heavens, which was treated as a separate discipline. Galileo insisted that his telescopic discoveries from 1609 onwards gave evidence for the Copernican cosmology and so thrust the telescope into the forefront of a dispute in natural philosophy, where its reliability as a tool of discovery would be a critical issue.

The telescope and the microscope created a new domain of instrumentation separate from the established trade of mathematical instruments. A different category of artisan, the more able and enterprising among the spectacle makers, produced the new optical instruments. Like the telescope, the microscope first arose in a commercial rather than a learned context. It was an optical toy with no agenda for use in natural philosophy until the mid-seventeenth century.

Then an increasing interest in explaining natural phenomena through the interaction of invisible particles acting as tiny machines made the microscope a likely arbitrator of the claims of the mechanical philosophy. Through the development of the microscope and telescope a new trade was born. By the late seventeenth century, although they included spectacles among their stock, some specialists had become "optical instrument makers."

The natural philosophers involved themselves closely in this development. Johannes Kepler and René Descartes had been concerned with the true form of an aplanatic lens, one that did not suffer from spherical aberration. Christopher Wren designed an unsuccessful machine for grinding hyperbolic lenses to remove the defect, while other early fellows of the Royal Society ground telescope objectives, as did Christiaan Huygens in the Netherlands. In the case of microscopes, Robert Hooke associated with the London makers and frequented their workshops, while in Delft Antoni van Leeuwenhoek made his own extraordinary microscopes with their single, tiny, spherical lenses. The best optical glass came from Italy, where Eustachio Divini in Rome and Giuseppe Campani in Bologna led the field. Italian natural philosophers, such as Gian Domenico Cassini for the telescope or Marcello Malpighi for the microscope, could rely on the products of the best commercial workshops. Leeuwenhoek had to make everything himself.

By the late seventeenth century, the commercial trade in optical instruments was particularly vigorous in London, where visitors to the shops of Christopher Cox, John Yarwell, or Richard Reeves might expect to buy a fine telescope or a microscope equivalent to the one illustrated in Hooke's *Micrographia* (1665). But the early promise of microscopes as arbitrator of philosophy proved hollow. If fleas and other tiny things were as complicated as they appeared to be, the fundamental mechanical corpuscles lay far beyond the instrument's reach. Microscopy declined in natural philosophy. Nonetheless Hooke's astonishing illustrations had made their mark: through much of the eighteenth century a widespread interest in natural history would supply the makers with a ready clientele for microscopes.

A third category of instrument with which the natural philosophers had an even stronger engagement than with optical instruments emerged in the later seventeenth century. These "instruments of natural philosophy," unlike the mathematical and optical ones, had no location of their own within the trade. Natural philosophers themselves designed the instruments and contracted assembly to artisans. Philosophical instruments included air pumps and electrical machines, which, unlike the passive telescopes and microscopes for observing, intervened and interfered with nature. They literally implemented the collaborative, public, and institutionalized experimental philosophy practiced in the Royal Society of London and other societies that cultivated natural knowledge. Experimental demonstrations were to be performed in public before witnesses and repeated at will: they created a need for instruments of natural philosophy.

Practical applications continued to drive improvements in mathematical instruments even while optical and philosophical instruments began to capture attention. Edmund Gunter in Gresham College, London devised a quadrant for telling the time and performing other astronomical calculations, a sector for navigating by the Mercator chart, and a rule for achieving the same end with logarithmic scales. The ubiquity and longevity of the "sliding Gunter" or logarithmic slide rule testify to the sophistication of mathematical instrumentation in the early-modern period.

As instruments changed over the seventeenth century so did their provenance and markets. London grew into a major center for instrument making and, in the eighteenth century, dominated the trade. Makers in London could belong to any guild or company—they could nominally be grocers, or haberdashers, or fishmongers—and the companies did not restrict the production methods, designs, or materials. This freedom, which contrasted with the centralized and regimented situation in Paris, suited a trade that needed to combine disparate materials, adopt new designs, adapt working practices, and merge artisanal skills. New configurations in the trade began to emerge, as certain London makers at the turn of the century, notably Edmund Culpeper and John Rowley, traded across the traditional boundaries by offering both mathematical and optical instruments.

During the eighteenth century, the most ambitious makers dealt in "mathematical, optical and natural philosophical instruments." Demonstration apparatus became fully commercial under the stimulus of subscription courses in experimental natural philosophy, such as those given by Francis Hauksbee in London and the abbé Jean-Antoine Nollet in Paris. Makers offered books (often written by themselves, in the cases of George Adams or Benjamin Martin), demonstrations, and courses of lectures in addition to instruments. Shops presented their wares within the context of the regu-

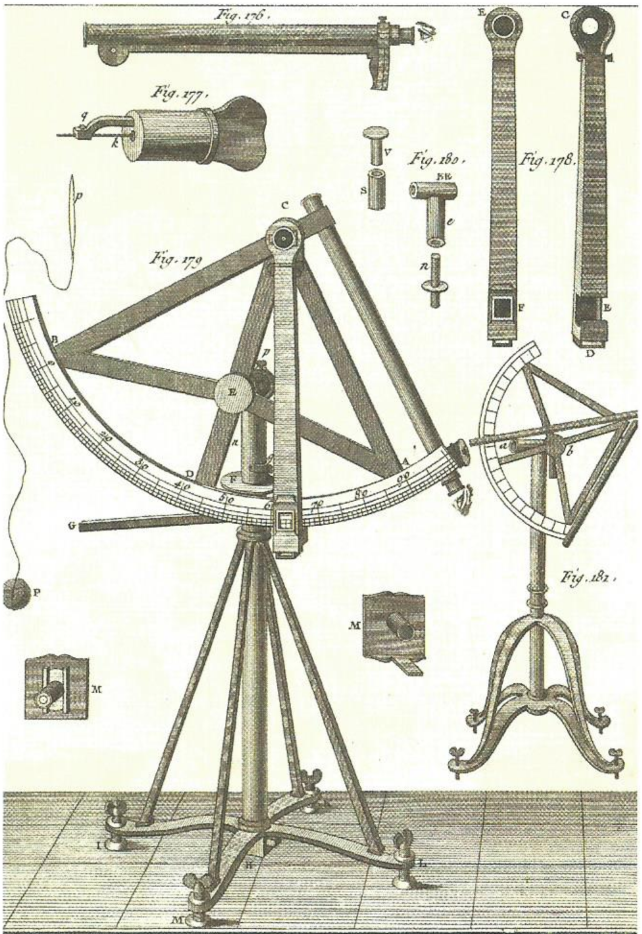


Fig. 176.
Fig. 177.
Fig. 178.
Fig. 179.
Fig. 180.
Fig. 181.
Astronomie, Quart de Cercle Mobile.
Benard dire.

Astronomical and geodetic instruments of the 17th and 18th century lar trade in luxury goods, intriguing foreign visitors. The growth of material consumption within the middle classes benefited the makers and natural philosophy had a fashionable following, encouraged by entertaining lecture courses or domestic demonstration from itinerant lecturers. The formation of instrument collections spread from institutions, universities, and the aristocracy to the homes of the bourgeoisie—a development encouraged by entrepreneurial traders in a buoyant market.

The rise of a consumer market directed the production of instruments toward the elegant, such as barometers, globes, and orreries, and the spectacular, such as air pumps and electrical machines. Telescopes, particularly the Gregorian reflector, and microscopes multiplied in the same context, and their designs reflected their intended station in a library or a drawing room. The solar microscope was developed to project large images of microscopic subjects onto a wall to entertain a group. At the same time, however, London manufacturers consolidated a leading position in the most exacting part of the trade: measuring instruments for astronomers, navigators, and surveyors.

A succession of outstanding makers of precision instruments in eighteenth-century London, beginning with George Graham and continuing through Jonathan and Jeremiah Sisson, John Bird, Jesse Ramsden, and John and Edward Troughton, raised the status of makers among the community of mathematicians and natural philosophers to an unprecedented level. These makers produced observatory instruments for fundamental measurement in astronomy—at first mural quadrants, transit instrument, and zenith and equatorial sectors, and later meridian circles—and sextants, theodolites, and other precision measuring instruments for everyday professional use. Their work was complemented by that of several outstanding optical instrument makers, John and Peter Dollond for lenses and James Short for telescope mirrors.

While individual skills must figure in the explanation of this development, certain institutional factors also played an important part—commissions from the Royal Observatory and later the Ordnance Survey, and the liberality of the Royal Society, which elected the leading makers as fellows, awarded them medals, and published their papers in the *Philosophical Transactions.* The activities of the Board of Longitude charged with administering the longitude prize established in 1714 were also influential. One of the contending methods, that of lunar distances, demanded exact and robust instruments. The board publicized methods it rewarded, for example, Bird's prescriptions for making quadrants.

At the end of the eighteenth century, makers began to move away from a concentration on handwork in small workshops. Jesse Ramsden employed some fifty men in his premises in Piccadilly; the Board of Longitude published his description of the dividing engine he built for the mechanical graduation of scales on sextants and other instruments. Hand division had previously been the most prized skill in the precision trade; it was now mechanized and, comparatively speaking, deskilled. Subcontracting, buying in parts, even buying whole instruments and adding the retailer's name, became common in the eighteenth century as the trade grew and its organization became more complex. These trends accelerated during the nineteenth century.

The acceleration proved costly to the London workshops. They lost their dominance, partly through complacency, partly through loss of status in the community of learning, partly through the vigorous rise of other centers of innovation. The downgrading of manual skill in the social changes brought by the industrial revolution may have been a factor in the loss of status, but the makers as individuals never regained their positions of respect. Even in astronomy, scientists with mechanical flair like George Biddell Airy designed the major instruments and commissioned components from different makers, adopting the division of labor from contemporary industry. Germany and France became increasingly competitive.

Munich was the center of the resurgent German industry. The able makers there included Georg von Reichenbach, Joseph Liebherr, Joseph von Utzschneider, Joseph Fraunhofer, Traugott Lebrecht Ertel, Georg Merz and Carl August, Ritter von Steinheil. They focused on precision instrumentation, which they pursued in partnerships of opticians and mechanicians. Thus they benefited from research-based improvements in glass quality as well as from innovative designs in structures and mountings. The workshop of the Repsold family formed another center in Hamburg, while Karl Philipp Heinrich Pistor and Johann August Daniel Oertling were active in Berlin from 1813 and 1826, respectively. Observatories, other than British ones, equipped in the nineteenth century usually had German instruments, whereas the many eighteenth-century foundations, including French ones, had been supplied from London.

The French Revolution swept away the old restrictive practices of the guilds and put in place reforms, such as the metric system of weights and measures, that would create work for instrument makers and encourage innovation. Étienne Lenoir, Jean Nicolas Fortin, and François-Antoine Jecker seized the new opportunities, supplied standards of length, weight, and capacity throughout the country, and met the renewed demand for portable instruments from mathematical professionals. Prominent and successful workshops in nineteenth-century France included Gambey, Lerebours and Secretan, Gautier, Morin, and others. The French developed a particular expertise in physical optics, led by Jules Duboscq and later by the aptly named Jean-Baptiste-François Soleil.

From 1851 onwards, international exhibitions furthered the international character of the instrument trade. The exhibitions' reports give a good indication of the relative strengths of the contributing nations. The British were taken aback at the success of their rivals at the Great Exhibition in London (1851). Microscopes, largely through the introduction of the achromatic objective, had again become serious tools of scientific research, and here London makers continued to shine; but elsewhere they had lost much ground. By the end of the century, the German workshops of Zeiss and Leitz had seized the lead in microscopy.

By 1900 the "scientific instrument" in the modern sense of the term had arrived. As makers sought to respond flexibly to rapid innovation, the old characterizations and distinctions became irrelevant. Spectroscopy opened up a vast new area of instrumentation for chemistry and astronomy. Industrial instruments greatly expanded the market open to instrument entrepreneurs, while the coming of the electrical industry and the spread of power supply, of the electric telegraph, and then of radio, opened up a large field for collaboration between scientists and manufacturers. Techniques of detection and measurement had not only to work on the laboratory bench, they had to be standardized and made sufficiently robust to travel successfully to distant stations.

The twentieth century was characterized by ever larger manufacturing units, close liaison with research laboratories in universities, in institutions, or in-house, a bewildering array of new techniques and instruments, and the growing irrelevance of regional contexts other than as economic determinants. This flexibility has been particularly marked as electronic technologies have increasingly displaced mechanical ones. Instrument making has become difficult to isolate from science itself. That may always have been the case. The ubiquity of instrumentation in today's science makes the relation obvious.

A further feature of the twentieth century was the rise of collecting, both institutional and private. Museums now have large collections of instruments—transferred to them from societies, universities, manufacturers, industries, collectors, dealers, and salesrooms. Historians have not realized the potential of this resource fully. Instruments have been integral to the story of science. Although material evidence may be more intractable and awkward to use than written sources, historians of science can scarcely afford to neglect it.

Jim Bennett

INSTRUMENTS, BIOLOGICAL. The fine woodcut representing a few dozen anatomy instruments—from the most delicate lancet to rough saw and hammer—included in Andreas Vesalius's epoch-making *On the Fabric of the Human Body* (1543) is an icon of the then new regard for instruments in the pursuit of natural knowledge. So too were the balance for measuring variations in weight owing to ingestion, excretion, and perspiration, discussed in Santorio Santorio's On *Static Medicine* (1614), and the diagrams describing simple loop and palpation experiments performed on the human body in William Harvey's *Movement of the Heart and Blood in Animals* (1628).

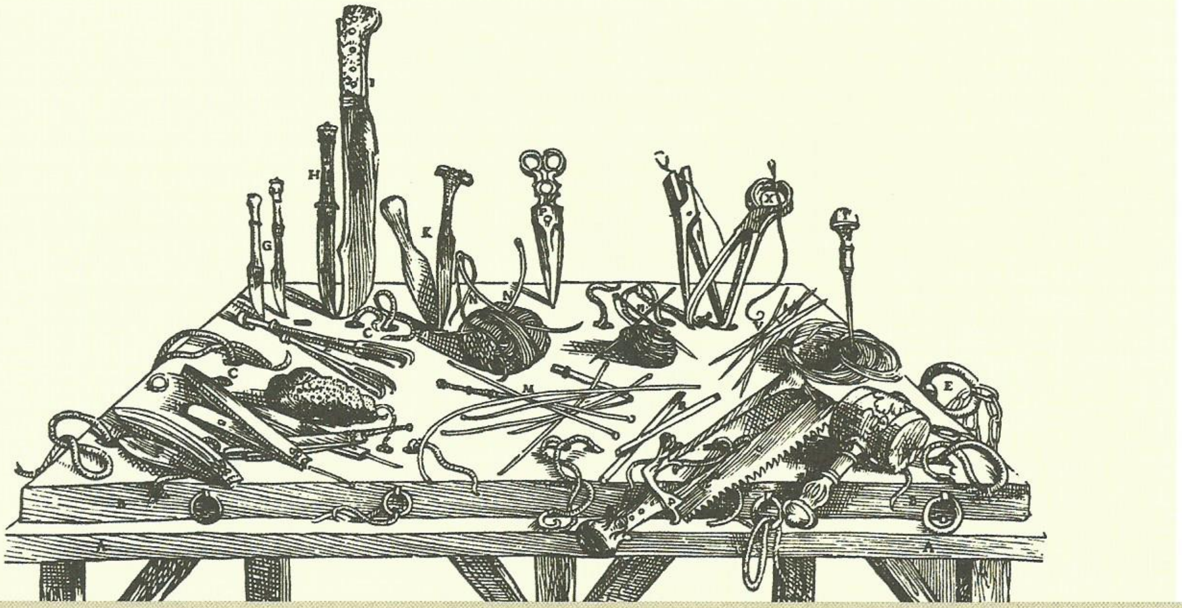
Many of the instruments represented by Vesalius, Santorio, and Harvey derived from established techniques in medicine, surgery, natural philosophy, alchemy, or chemistry. The same applied to several instruments used by early modern naturalists, which came from pharmacy, agriculture, hunting, breeding, and the multifaceted know-how of merchants and travelers. The emphasis on instruments, however, was new, and it affected the study of living things just as it did astronomy and other sciences infused with the "new philosophy." The positive evaluation of artisanal skills extended to cooperation with printers to employ the latest advances in the art to represent and spread knowledge and achievements—a trend from which anatomy, natural history, and printing itself benefited in turn.

From the 1620s, a genuinely new instrument became an icon of what later would be called the life or biological sciences. This was the optical microscope, put to good use after 1660 by Robert Hooke, Marcello Malpighi, and Nehemiah Grew. Meanwhile the "mechanical philosophy" penetrated the study of plant and animal life. The air pump played a role when Robert Boyle showed that plants produce air (1680–1682). John Mayow and others used simple cupping glasses and siphon arrangements for similar purposes. But perhaps no one better than Stephen Hales, with his *Vegetable Staticks* (1728) and *Haemastaticks* (1733), conveyed Europe-wide the notion that organisms could be included in experimental apparatus that could measure the movements and pressure of blood or sap, and the quantification of the airs inspired, expired, and transpired.

The study of the chemistry of life throughout the eighteenth century continued to demand new instrumentation. Apparatus developed by chemists became basic tools for investigators exploring animal heat and respiration. The thermometer and the calorimeter have remained fundamental for physiology to the present. The stethoscope came in 1816.

Electrical machines were adapted to the investigation and possible improvement of living organisms after the invention of the Leyden jar. With the rise of Galvanism and the invention of the voltaic battery in 1799, electric currents became available. From the 1840s, galvanometers—based on the deflection of a compass needle by a wire carrying a current, and developed mainly in connection with telegraphy—allowed scientists like Emil du Bois-Reymond to carry out new measurements of the small quantities of electricity involved in physiological processes.

The family of electrical measuring devices used in physiology expanded quickly after 1850. In 1855 Rudolf Albert von Koelliker and Heinrich Müller argued that electrical activity must accompany the functioning of the vertebrate



Dissecting tools pictured in Andreas Vesalius, *De humani corporis fabrica* (1543) heart. In 1874, physicist Gabriel Jonas Lippmann introduced the capillary electrometer based on the response of the surface tension and thus the shape of the meniscus of mercury to a change in electromotive force of as little as 0.0001 volt. Étienne-Jules Marey applied the instrument to the study of muscles, where the quick reactions of the new electrometer made it possible to distinguish individual muscle-action potentials, which the galvanometer did not. Photographic recording devices adapted to the electrometer allowed Lippmann and Marey, in 1876, to record the changes of the electromotive force in the contracting heart of a tortoise and a frog, producing the first electrocardiograms. Further improvements enabled Augustus D. Waller, in 1887, to obtain the first human electrocardiogram.

In the 1840s, another new family of apparatus had been introduced—pneumatic and mechanical instruments used to study the combined action of respiration and the systolic and diastolic rhythms of the heart. The first such device, Carl Ludwig's kymograph (from the Greek *kyma,* "wave"), combined a manometer connected to the artery and clockwork moving a recording cylinder (1846). The self-registering apparatus was inspired by the indicators that James Watt used to chart pressure variations in a steam engine. The myograph (for taking tracings of muscular contractions and relaxation), the sphygmograph (for recording the movements of the pulse), and the cardiograph followed soon.

Important improvements introduced after 1830 in microscopes (correction of spherical aberration), the preparation of specimens (better microtomes and staining techniques), and microsurgery facilitated an unprecedented flow of microscopic observations that molded the content, laboratory set-up, and teaching habits in cytology, histology, embryology, and neurology through the mid-twentieth century. Similar effects on research, training, and manipulative skills were produced after the mid-nineteenth century in botany, entomology, zoology, paleontology, and anthropology by the creation of natural history museums, agricultural experiment stations, and oceanographic institutes.

Physiology and clinical medicine found new opportunities for instrumental developments after 1900 with the introduction of new electromagnetic apparatus. Willem Einthoven's string galvanometer (1903) made possible the first complete electrocardiograph, produced by Cambridge Scientific Instruments in 1908. Einthoven's machine, filling two rooms, evidently was big science. Soon, however, the introduction of vacuum-tube amplifiers developed for radio communications allowed the production of more practical, and less expensive electrophysiological and medical apparatus based on electronic technology, setting a pattern of exchange that has continued to the present.

Also in the 1920s, the ultracentrifuge—in which an oil-turbine generated gravitational fields reaching 400,000 *g* by the 1940s—was developed by The Svedberg. Meant to determine the size of colloidal particles, the ultracentrifuge proved essential for the study of hemoglobin and proteins. Later versions have become popular instruments in biochemical laboratories. So have electrophoresis machines, beginning with those produced by Arne Tiselius in the 1930s. Since World War II these machines—together with X-ray diffraction installations, electron microscopes, electronic cell counters, flow cytometers, fluorescent-activated cell sorters, radioactive tracers, and peptide synthesizers—have reshaped life science laboratories. The new physical apparatus and some old and new laboratory animals, such as the mouse (*Mus musculus*), the fruit fly (*Drosophila melanogaster*), the bacterium *Escherichia coli,* and the fungus *Neurospora crassa,* have changed the sociology as well as the layout of the laboratory.

The development of biotechnologies since the 1960s and genomics in the 1990s have brought an impressive host of new instruments: protein sequencers, peptide synthesizers, gene or DNA sequencers, biolistic apparatus (or "gene guns," using microprojectiles to inject DNA into cells), patch clamp amplifiers (measuring minute membrane cell currents), and polymerase chain reaction machines (to identify and reproduce a gene or a segment of DNA). Concomitantly, information technology has come to play an increasingly important role in biology. Magnetic resonance imaging, and computerized tomography scanners have reshaped hospital, clinical, and patient practice.

With U.S. industry analysts expecting a 12 percent per year increase in the market for life science instrumentation in universities and other schools between 1998 and 2003, and with the related market in hospital and clinical research instrumentation expected to grow at 48 percent per year, biological instruments are more than ever industrial, as well as research, assets.

GIULIANO PANCALDI

INSTRUMENTS, ELECTRICAL MEASURING

Electrometers

Until the invention of the electric cell by Alessandro Volta in 1800, studies of electricity concerned only electrostatics. The first electrical measuring devices quantified the amount of electricity produced by a frictional machine or stored in a Leyden jar. Although various electroscopes and electrometers had been in use since the 1740s, electricians (as they called themselves) lacked fundamental concepts of charge, tension, and capacity, and had not defined their units of measurement. The first instruments divide into three main groups in accordance with their principle of operation: electrostatic attraction and repulsion, spark length, and heating effects of discharges. The first group includes all the electroscopes with suspended balls, metallic strips, or movable pointers. Of the many types proposed during the later eighteenth century, those of John Canton (pith balls), Abraham Bennet (gold leaves), and Volta (straws) deserve special mention. These instruments were neither comparable nor absolute. The other groups include Timothy Lane's discharging electroscope (spark length) and Ebenezer Kinnersley's "electrical thermometer" (heating effect).

In the last quarter of the eighteenth century, electrostatics became increasingly quantitative. Volta managed to make his straw electrometers comparable to one another and almost proportional to the intensity measured. By adding a condenser to his electroscopes Volta increased their sensitivity and detected the weak contact potential between two metals. It was a fundamental step leading to his discovery of the electrochemical pile.

Between the end of the eighteenth century and the first decades of the nineteenth century electrostatics became highly mathematized by Simeon-Denis Poisson and others who built on the laws of force demonstrated by Charles Augustin Coulomb. New types of electroscopes were introduced. The most important later models derived from the absolute galvanometer (and its reduced form, the portable electrometer) developed by William Thomson, Lord Kelvin, after 1850. It used the attraction of two metallic disks. Thomson also designed a quadrant electrometer in which a large suspended aluminum needle moved between four insulated brass quadrants. This instrument, often modified and improved, remained in use well into the twentieth century.

Galvanometers

In 1820, the Danish natural philosopher Hans Christian Oersted published the description of his experiments demonstrating that an electric current can deflect a magnetic needle. Johann S. Schweigger, Johann Poggendorff, and James Cumming soon introduced current multipliers, essentially copper wires coiled around a magnetic needle. The coil increased the action of the current on the magnet. These simple galvanoscopes were followed by "astatic" ones designed by Leopoldo Nobili around 1823. Nobili suspended a pair of identical and parallel needles with like poles pointing in opposite directions. He inserted the lower needle into the multiplying coil and used the upper one as an indicating pointer on a circular scale. Thanks to this system, Nobili's galvanometers did not respond to the earth's magnetism. They underwent many important improvements during the nineteenth century.

In 1837, the French physicist Claude Pouillet invented the tangent and sine galvanometers, the first devices for measuring absolute current. Here the action of a current flowing in a circular coil around a magnetic needle counterbalances the action of the earth's magnetism. Owing to their simple geometry, Pouillet's galvanometers allowed the measurement of a current in terms of the dimensions of the coil, the intensity of the earth's magnetic field, and the deflection of the needle. The absolute electrodynamometer of Wilhelm Weber (1845) had a movable coil in the center of a larger, fixed one. This instrument does not require one to know the value of the earth's magnetism and can also measure alternating currents.

The development of telegraphy, the laying of the first transatlantic cable in 1858, and the need to define electric standards produced great advances in galvanometry. Detecting the weak and damped signal transmitted by the cable engineers needed a very sensitive, quick, and robust instrument. William Thomson designed a moving magnet galvanometer that met all these requirements. He suspended a tiny magnet with a small mirror attached and magnified its deflections by reflecting a ray of light onto a scale. Thomson subsequently introduced a multiple magnet astatic version of his instrument.

Moving coil galvanometers had been in use since the 1820s, but Thomson's telegraphic siphon recorder of 1867 was the first commercial instrument of this type. In 1885, the French physicist and physiologist Arsène d'Arsonval together with the electrician Marcel Deprez, designed a galvanometer of the same type that found widespread use. It employed a light rectangular coil hanging between the poles of a powerful permanent magnet as the current detector.

Another popular late revival was the string galvanometer with a light, current-carrying metallic wire as the detector. First proposed in 1827, greatly improved by Willem Einthoven around 1900, and used in the first electrocardiographs, the string galvanometer, duly modified, figured in the oscillographs invented by William du Bois Duddell at the end of the nineteenth century.

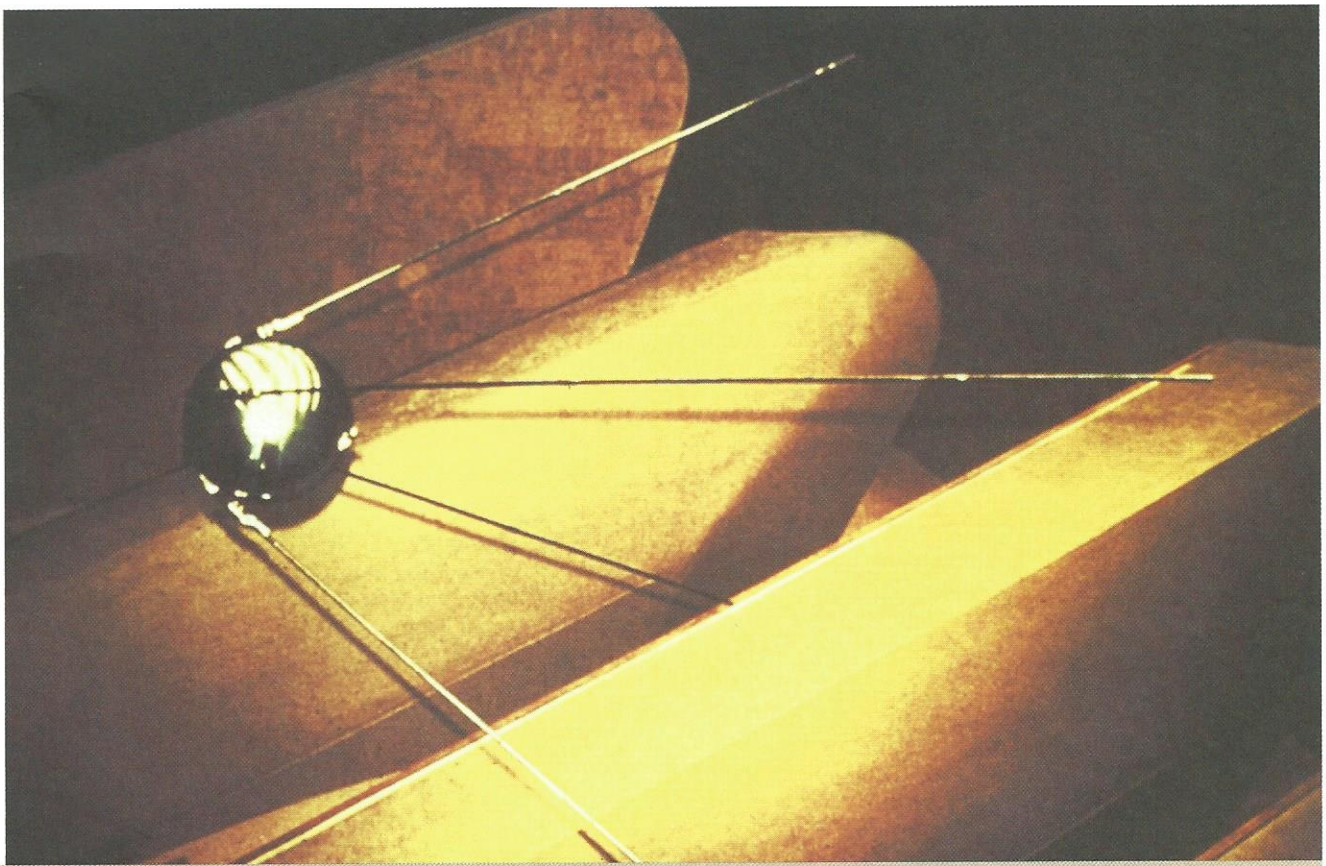
Sophisticated current balances, based on electrodynamic action between movable and fixed coils, were used for high precision laboratory measurements. The indefatigable Thomson devised a series of such instruments in the 1880s for use as secondary standards for calibrating others' instruments. Additional clever nineteenth-century instruments included the "Wheatstone bridge," invented in 1843 by the English physicist Charles Wheatstone, who developed the idea from Samuel H. Christie. This bridge amounts to a circuit including a sensitive galvanometer. It enables one to determine the value of unknown resistances by balancing currents to sire a zero reading on the galvanometer.

Industrial Instruments: Ammeters, Voltmeters, and Supply Meters

The rise of the electrical industry required new and robust measurement instruments that would be easy to operate. In the early 1880s, the English physicists William Ayrton and John Perry produced a moving iron ammeter, which sucked a piece of iron, connected to a helical spring, into a current-carrying solenoid. When the iron was attracted in the solenoid, the spring uncoiled and moved a pointer which was fixed to it. Similar apparatus with a much higher internal resistance absorbed a very small amount of current and served as voltmeters. In 1888, instruments patented by the British engineer Edward Weston began to supersede these instruments. Weston's ammeters and voltmeters had a pivoted moving coil between the poles of a strong permanent magnet. The instrument maker Robert Paul at the beginning of the twentieth century introduced the low-friction moving coil unipivot meter, which did not require accurate leveling. Although these instruments only measured direct current (DC), they continued to be widely used in the twentieth century.

For alternating current (AC), the German firm Simens and Halske, and then Weston and others, introduced compact electrodynamometers. A small moveable coil was inserted in a larger fixed coil. The coils were connected in series, and a current flowing through them produced a deflection of the moveable one. Thermal (hot wire) instruments became essential for measuring high-frequency currents, when solenoids and coils present high inductances. Philip Cardew patented the first practical apparatus of this kind in 1883; Hartmann and Braun produced a more compact and successful design in the 1890s. Voltage could be measured with a galvanometric voltmeter (fundamentally an ammeter with a very high internal resistance) or with an electrostatic voltmeter of the types invented by Thomson.

Dial of a voltmeter manufactured by the Schuckert firm ca. 1890



The Sputnik satellite, launched during the International Geophysical Year, began the space race.

The use of shunts made possible measurement of currents of widely differing magnitudes.

The introduction of electric light in the 1880s and the distribution of electricity to private customers required apparatus for measuring and recording the amount of electric energy supplied to the users. Thomas Edison patented the first electrolytic supply meter and Hermann Aaron invented an electricity-driven pendulum clock system, while others introduced electric motor meters operating against an electromagnetic brake. With the increasing use of AC, the induction-motor meters became standard for measuring domestic electricity consumption. Electronic supply meters, introduced in the 1980s, are now used for industrial applications.

The invention of the thermoionic valve revolutionized the technology of electrical measurement. In the 1920s, the first meters using thermoionic elements were introduced. Electronic oscilloscopes replaced electromechanical models, DC amplifiers increased sensitivity, and copper oxide rectifiers and diodes adjusted DC instruments for AC. In the second half of the twentieth century, solid-state transistors and miniaturized circuits created the possibility of a new generation of instruments. Voltage could be converted into time intervals and measured with a quartz-controlled clock. Today cheap electronic multimeters with digital displays can measure voltages, resistances, capacities, and so on in DC or AC.

Paolo Brennt

INTERNATIONAL GEOPHYSICAL YEAR. The International Geophysical Year (IGY) was an ambitious international scientific project that ran from July 1957 to December 1958. In 1950, American geophysicists had proposed a Third International Polar Year that would make significant advances on the earlier ones of 1882–1883 and 1932–1933 by using the rocketry, information processing, and other instrumentation developed during World War II. The project quickly widened to geophysics as a whole. Sanctioned by the International Council of Scientific Unions—the parent body of international scientific organizations—and implemented by national committees in participating countries, it involved some eight thousand scientists from about sixty different nations. It was timed to coincide with the twenty-fifth anniversary of the Second International Polar Year and with a peak in the sunspot cycle.

The IGY Special Committee decided to concentrate on the topics most likely to benefit from a global approach: aurora and airglow, cosmic rays, geomagnetism, glaciology, gravity, ionospheric physics, longitude and latitude determinations, meteorology, oceanography, seismology, and solar activity. The project produced an unparalleled database as well as a number of major discoveries. Oceanographers confirmed the existence of a continuous worldwide system of submarine midocean ridges (actually huge mountain chains), one piece of evidence that contributed to plate tectonics in the mid–1970s. Satellites launched by the United States detected belts of radiation around the earth (named the Van Allen belts) and the influx of charged solar particles believed to be responsible for the auroras. Scientists in Antarctica determined the size and shape of the land mass underlying the ice and discovered a jet stream circling the continent.

The IGY was a prime example of "big science." Governments contributed major funding. Scientists participated in much larger numbers than had been normal in peacetime. International cooperation led to the invention and dissemination of new, intricate, and very expensive instruments. Scientists became more involved in and gained new standing in politics and international law. IGY's success encouraged the United States to commit to Skylab; it led to more intense Antarctic exploration; and it prompted further international cooperation in the International Year of the Quiet Sun (1964–1965), the International Hydro-logical Decade (1965–1975), and the International Decade of Ocean Exploration (1970–1980).

The two-China problem, competition in Antarctica, and the space race exemplify relations between politics and the IGY. In 1955, the People's Republic of China agreed to join the IGY. Two years later, on learning that the Nationalist Chinese of Taiwan had belatedly signed on, the communist government backed out. Scientists on the mainland decided to go ahead with the research even though they could not do so under the umbrella of the IGY. In the case of Antarctica, seven countries that had been asserting territorial claims agreed to set them aside for the duration of the IGY. Eleven nations cooperated in establishing fifty-five research stations. The nations shared logistical support, which their militaries often provided. Although these complex arrangements caused some tensions, the experiment succeeded sufficiently that in December 1959 the Antarctic Treaty was signed preserving the continent for the purposes of peaceful scientific research.

The space race dates from 4 October 1957 when the Soviets successfully launched *Sputnik*, the first artificial satellite to circle the Earth, and part of the IGY. From then on scientists used data gathered by both Soviet and U.S. satellites, supposedly freely circulated through three centers, one in Moscow, one in Washington, and one divided among several other nations. The Soviets, however, who used military rockets to launch satellites, did not release data about their launch vehicles, and the U.S. government suppressed information about their bomb tests, even as IGY scientists detected the effects. In China, Antarctica, and during the space race, scientists had to learn to cope with a world in which science was no ivory tower activity but deeply enmeshed in politics. The history of the IGY is ripe with implications for the politics and sociology of science as well as information about the postwar explosion in earth and planetary sciences.

RACHEL LAUDAN

INTERNATIONAL ORGANIZATIONS. International science organizations are ideologically motivated by belief in the unity of nature, the universe, and scientific laws. Despite criticisms from social constructivists, universalism motivates internationalism. While coexisting with other knowledge forms, modern science was founded on ideas coming from several cultures and traditions, being thus international at its inception. Early examples include the international meteorological project started by James Jurin, secretary of the Royal Society of London in 1723. Observations of the transits of Venus in 1761 and 1769, coordinated by the Frenchman Joseph Delisle, involved Italians, Portuguese, Spaniards, Russians, Danes, and Swedes as well as the French and English, who happened then to be at war.

During the nineteenth century science took on a more national cast, with attendant glories and declines. National scientific associations emerged. The British Association for the Advancement of Science was founded in 1831, its German counterpoint in 1822, its American in 1848, and the Indian Association of Cultivation of Science in 1876. Scientific rivalries mirrored diplomatic relations. Internationalist impulses balanced these nationalist trends as even national efforts could contribute to international science. The metric system, invented and promoted by the French, prevailed throughout Europe. The Conférence Diplomatique du Mètre (1875) resulted in the creation of the International Bureau of Weights and Measures located at Sèvres.

International meetings sought to transcend national borders. International congresses of chemists met in 1860, of geologists in 1875, and of physicists in 1900. Universal exhibitions, such as Paris 1889 and 1900, included scientific sessions. International committees deliberated standards and nomenclature (for example, electrical units and atomic weights). Reacting to the growing nationalist sentiments of the time, many scientists adopted internationalist ideals by the end of the nineteenth century, culminating in the foundation of the International Association of Academies (IAA) in 1899. However, most of these early international associations succumbed in World War I. Science became a war instrument, and scientists national propagandists, as in the "Appeal of the 93 Intellectuals" defending German war aims (October 1914) and counter-manifestos issued by the Allies. Similarly, the Allied position against Germany in 1918 led in 1919 to the formation of the International Research Council (IRC) from which the former Central Powers were excluded until 1926. The coming to power of the Nazis in 1933 and rearmament snuffed out the brief interwar interlude of renewed internationalist impulses.

Twentieth-century scientific internationalism, however, worked to counterbalance the destructive association of science and the state. The number of international scientific meetings is revealing: 20 between 1870 and 1900,14 between 1901 and 1914, 7 during the war, 15 between 1918 and 1923, and 45 in the early 1930s. Similarly, international organizations proliferated after 1918, fostering research and the free mobility of scientists. The International Union of Pure and Applied Chemistry (IUPAC), the International Union of Biological Sciences (IUBS), and the International Astronomical Union (IAU) were founded in 1919; the physicists followed with the International Union of Pure and Applied Physics (IUPAP) in 1922. The International Council of Scientific Unions (ICSU) replaced the IRC in 1931; its founders insisted that science was nonpolitical and universal. Scientists set the basis for the internationalism of UNESCO and other UN organizations after World War II. The experiences of UNESCO and the United Nations Atomic Energy Commission (UNAEC) indicate the opportunities and perils of international organizations during the later twentieth century.

The UN General Assembly created the UNAEC as its exclusive agent in the field, with a mandate to create mechanisms for research and control of atomic energy and for the elimination of nuclear armaments. UNAEC's initiatives, however, were curtailed by the Security Council's veto power and it became a venue for nationalism. At the first UNAEC meetings, held in June 1946, the U.S. representative, Bernard Baruch, insisted on the veto, controls, and sanctions. The Soviets asked for the destruction of nuclear weapons. The French argued that it was necessary to determine the limits of the scientifically possible.

To complicate UNAEC activities, in July 1946 the United States tested improved nuclear devices at Bikini and in August passed the Atomic Energy Act imposing rigid controls on nuclear material. Despite a growing air of futility, the commission announced that international controls were still possible given enough safeguards. In November, the UNAEC presented a progress report to the Security Council. Despite French protests, armaments debate focussed on atomic weapons. The General Assembly demanded an atomic control convention from the Security Council. In December the UNAEC approved Baruch's proposal calling for a system to outlaw atomic weapons and instruments to enforce the system. The report was approved, Poland and the USSR abstaining. The commission submitted Baruch's recommendations to the Security Council.

Considering his job done, Baruch resigned in January 1947. His plan got nowhere. In February Andrey Gromyko proposed a convention prohibiting atomic weapons, the destruction of existing stockpiles, an international control system, and an international organization for atomic energy research. The Cold War gave little chance for an agreement. The UNAEC assembled for the last time on 29 July 1949. On 23 August the Soviet Union detonated its first atomic bomb.

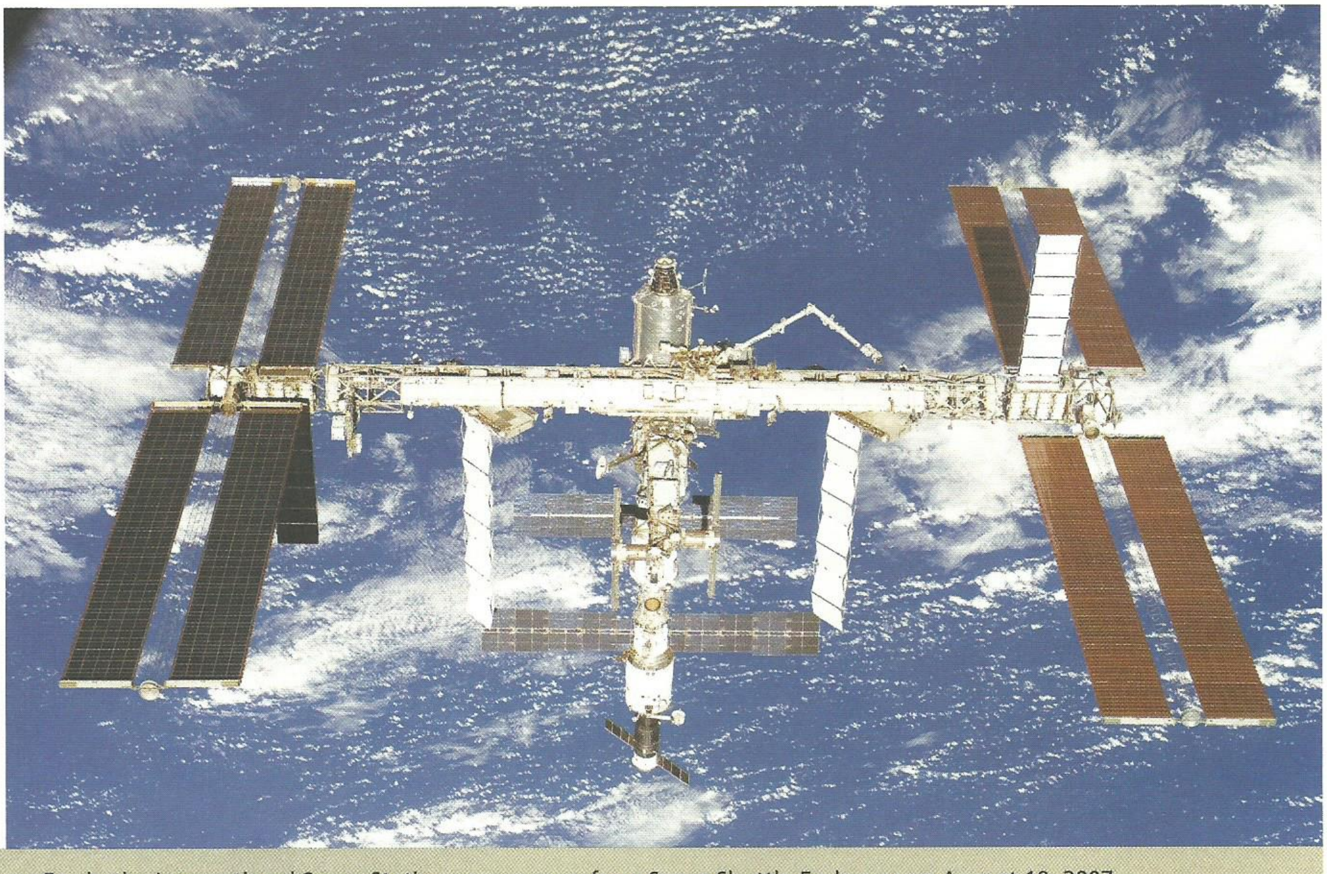
The short lived and nearly forgotten UNAEC was superseded by the International Atomic Energy Agency. However, the United Nations now operates on atomic energy matters along the lines UNAEC discussed. No "illegal" atomic operations are allowed, and no atomic wars have occurred. By denying their national affiliation and working directly within the structure of the UNAEC, scientists reinforced the highest internationalist ideals and achieved long-term results. Despite this success, the story of UNAEC-IAEC shows that science can easily become a theater for international conflict. The history of UNESCO illustrates the point from a different perspective.

UNESCO was preceded by the International Committee of Intellectual Co-operation, founded in 1922 and based in Geneva, and its executive agency, the International Institute of Intellectual Co-operation, founded in 1925 and based in Paris. Both existed until 1946. UNESCO had another precursor in the International Bureau of Education (IBE) founded in 1925 and based in Geneva. IBE became part of UNESCO in 1969. In November 1945, the London Conference of Allied Ministers of Education approved UNESCO's constitution. It entered into effect in November 1946. One of UNESCO's five main functions is the advancement, transfer, and sharing of knowledge.

UNESCO comprises three bodies. The General Conference, composed of member states, approves the biannual program and budget. The Executive Board, composed of fifty-eight representatives, meets twice a year and functions as an administrative council, supervising the program's execution. The Secretariat is appointed every six years. UNESCO is supported by national commissions, nearly seven thousand schools, and over six thousand clubs and associations.

UNESCO's impressive achievements include a vast publishing program, over ten thousand titles between 1946 and 2000, among them the *World Science Report* and the *UNESCO Courier,* issued in twenty-seven languages. Membership increased steadily until 1980, when a crisis of credibility hit. The United States, Great Britain, and Singapore left in 1984 and 1985 (membership nonetheless rose from 153 in 1980 to 159 in 1990). When the crisis ended, numbers again increased rapidly, reaching 188 in 2000.

The Americans and the British quit UNESCO because they thought that its programs threatened their national interests. For them, UNESCO did not use its resources neutrally. Unable to convince the majority of the UNESCO assembly, they withdrew, thereby creating a stronger and more internationalist organization. Politically motivated projects declined, efficiency improved, and hiring processes became visible as other nations moved in to keep the dream of international science and education alive. Federico Mayor (Spain) returned UNESCO to political neutrality during



High over Earth, the International Space Station moves away from Space Shuttle Endeavor on August 19, 2007 his term (1987–1999). Improvements continued, made easier by the dissolution of the Soviet Union.

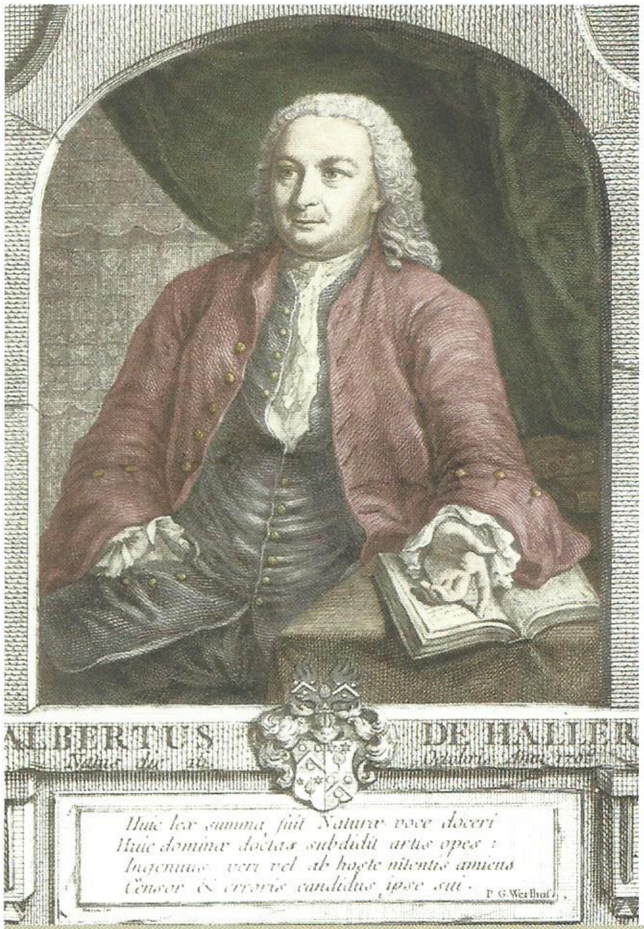
In the early twenty-first century the excessive emphasis on applications and financial gains may be more threatening to internationalism than nationalism. The problem obtrudes in the two great human adventures that survived the Cold War, polar research and the International Space Station. Polar research must be international because of the nature of the problems and demands on resources. Nationalistic positions are irrelevant in conflicts between different disciplines over the uses of research vessels, logistics, and instruments. Like polar research, national competition marked the early history of space exploration. Space research has always been very close to military applications. Nevertheless, most regard Yuri Gagarin and Neil Armstrong as individual astronauts, not as flag carriers. They have been taken out of their nationalist contexts to become international symbols. The International Space Station (ISS) may open a new chapter in the history of humanity. By confronting research issues above the planet, ISS reinforces the unity of human society and raises interesting possibilities for a reinterpretation of history.

Regis Cabral

IRRITABILITY. Physiologists and biologists have used the term "irritability" to denote the property of organs, tissues, living matter, and protoplasm that allows their stimulation or excitation. According to ancient physiological doctrines, the irritated part must be able to recognize being irritated in order to respond. Hence Galen (129/130–199/200) assigned a kind of "perception" not only to the nervous system, but also to organs like the stomach, uterus, and bladder, and why the notion of irritability was often associated with that of sensation, perception, and sensibility during the seventeenth and eighteenth centuries.

Building upon ancient doctrines and contemporary experiments, both William Harvey and Frances Glisson put forward doctrines of irritation. In his early work *Anatomia hepatis* (1654), Glisson maintained that the stomach and intestines expelled harmful agents because these organs were "capable of irritation." In his *Tractatus de ventriculo et intestinis* (1672) he shifted from a doctrine of irritation to one of irritability by assigning to fibers a "natural perception" independent of nerves, so that they could be irritated and respond to such irritation. This property he called irritability.

Glisson's doctrine lapsed into oblivion, until its partial revival by Albrecht von Haller in a paper published in Göttingen in 1753 ("De partibus corporis humani sensilibus et irritabilibus"). Haller suggested "a new division of the parts of the human body" based on experiments carried out mainly on living animals and consisting in diversified stimulation of different parts of the animal body. Haller named irritable any part that contracted when touched, and sensible any part that evidenced signs of pain. Since all parts displaying irritability were muscular, and those displaying sensibility were nervous, Haller stated that both properties depended "on the original fabric of the parts." In so doing he correlated a specific physiological behavior with a specific tissue structure.


ALBERTUS DE HALLER
Huic lex summa fuit Naturæ voce doceri
Huic dominæ doctas subdidit artis opes :
Ingenuus veri vel ab hoste nitentis amicus
Censor & erroris candidus ipse sui.
P. G. Werlhof

Albrecht von Haller (1708–1777), Swiss anatomist and polymath

Haller's doctrine aroused blazing controversy for over twenty years. Robert Whytt contested Haller's clear-cut distinction between irritability and sensibility in his *Physiological Essays* (1755), maintaining that muscular contractions arise from their sensibility and "are no more than an effort of nature to throw off what is hurtful." Felice Fontana investigated the laws of irritability, or muscular contraction, and discovered that the heart loses irritability during contraction, a phenomenon later named the refractory period of the heart (*De irritabilitatis legibus,* 1767).

By the early nineteenth century, the notions of irritability and sensibility had been incorporated into most physiological systems. Some authors applied them also to plant physiology. However, while contractility replaced irritability in Haller's sense, biologists like Jean Baptiste Lamarck considered irritability to be the fundamental property that distinguished animals from vegetables. During the second half of the nineteenth century, irritability was assigned to the protoplasm of cells. By the early twentieth century, it concerned the response of all living cells and organisms to change in their environment, and was increasingly replaced by the term "excitability."

Renato G. Mazzolini

J

JOURNAL. The scientific journal and its essential companion, the journal article, have continuously grown in importance since their debut in the mid-seventeenth century. As the word "journal"—and its substitute, "periodical"—suggest, this medium is characterized by currency and regularity of publication. Correspondence, appendices or revisions of books, and even manuscripts predated the journal as methods for communicating scientific news, but none of these formats could match the stability of the journal as a repository for the rapidly growing scientific literature.

The first regularly published periodical to include scientific essays and reviews was the *Journal des Sçavans,* which began publication on 5 January 1665. It was followed later that year by the first journal to specialize in experimental science and natural philosophy, the *Philosophical Transactions* of the Royal Society of London. Its articles generally reported briefly on experiments or observations, fresh and accessible material appropriate for prompt publication. Founded in 1682, the *Acta Eruditorum* of the Academia Naturae Curiosorum, by publishing in Latin, attracted articles in academic fields such as mathematics.

During the eighteenth century, the founding of hundreds of new scientific academies and societies paced the proliferation of scientific journals and concentrated the control of the scientific community over its burgeoning literature. One of the most tangible steps taken by these institutions was to provide opportunities for the dissemination of knowledge. The Paris Academy of Sciences, after reorganizing in 1699, established a record of its accomplishments through the *Histoire,* an annual publication required by the Crown, and the *Mémoires* written by individual members, reviewed by the assembly, and issued with the *Histoire* beginning in 1701. Societies sought to stimulate discoveries, inventions, and improvements through open communication of results; the successful ones created a readership of correspondents, professors, officials, agronomists, physicians, and others who consumed and contributed to their programs. Most smaller societies and academies in the eighteenth century, especially those in the German states, adhered more closely to the Royal Society's model of prompt publication than the Paris Academy's deliberate transactions, but not without borrowing from the Paris model the practice of explicit institutional affiliation with their journals.

This same period witnessed two more trends in journal publishing: the proliferation of privately published journals and specialization. The two trends were linked, if only because academies and societies with their learned memberships usually supported journals covering the whole of science, while independent publishers often followed more narrowly defined interests. Journals setting the latter trend were the Abbé Rozier's *Introduction aux observations sur la physique* (later the *Journal de physique),* founded in 1771; *Der Naturforscher,* founded in 1774 and edited by J. E. I. Walch; and William Nicholson's *Journal of Natural Philosophy, Chemistry, and the Arts,* founded in 1797 and more commonly known as "Nicholson's Journal." While these viewed all of experimental science as their domain, other journals in chemistry, forestry, natural history, mining, medicine, and additional fields sharpened the focus more narrowly. Private journals covering general science reached their high point by the mid-nineteenth century, then were overwhelmed by institutionally sponsored and single-discipline journals. The *Philosophical Magazine,* founded by Alexander Tilloch in 1798, exemplified this pattern by reducing its coverage gradually to physics research and by swallowing Nicholson's Journal. While the publications of academies continued to cover the sciences generally, a parallel trend toward the division of transactions along disciplinary lines emerged, led by the voluminous *Comptes Rendus* of the Paris Academy. Conferences became an important means of semiformal communication among scientists, and their proceedings joined journals in the publication of contributions. By the early twentieth century, the article and conference paper dominated formal scientific communication.

The growth of the journal literature encouraged innovations in bibliographic control of these publications. By the end of the eighteenth century, the expense and number of periodicals made it difficult for any individual to survey the literature, let alone acquire it. Annual and multiyear indexes for periodicals and review journals such as Lorenz Crell's *Chemisches Journal* (1778–1781) covered the literature and followed the example of the *Allgemeine Deutsche Bibliothek* (1765–1792) by providing intellectual access in the form of indexes. By the end of the century, review journals and analytical bibliographies of periodical literature began to appear, culminating in the *Allgemeines Repertorium der Literatur* of Johann Samuel Ersch, published between 1793 and 1807 to cover publications from 1785 to 1800. Indexes, bibliographies, and biobibliographies edited by Ersch, Johann Poggendorff, Georg Christoph Hamberger, and others prepared the way for comprehensive indexes to the scientific literature such as the *Royal Society Catalogue of Scientific Papers,* covering the entire nineteenth century; its successor, the *International Catalogue of Scientific Literature,* continuing to the beginning of World War I; *Science Abstracts,* which began publication in 1898; *Chemical Abstracts,* founded in 1907; and dozens of others. By 1960, *Science Abstracts* alone generated about 21,000 citations with abstracts annually, and *Chemical Abstracts* occupied roughly 3,000 abstractors. With the rise of bibliometrics, new forms of bibliographic control such as citation indexes, offered in Eugene Garfield's *Sci-*

ence Citation Index since 1961, navigated a vast sea of citations. As the literature grew, abstracting and bibliographic services such as the INSPEC (Information Service in Physics, Electrotechnology, and Control) database *(Science Abstracts)* began to depend on computers to deliver searchable bibliographic databases. By the beginning of the twentieth century, printed books had yielded their central position in scientific communication to the journal, conference paper, and preprint. Issues of quality control, economics, and technology shaped the journal in this century. The system of peer review that evolved over the course of the century gave intellectual control of journal contents to editors and reviewers representing the ranks of scientists. The challenge of managing the expense of publication proved more difficult as the size of the published literature grew. One solution, represented by the founding of the American Institute of Physics in 1932, was to concentrate nonprofit publishing by member societies. But since the 1950s consolidation has favored private publishers such as Reed Elsevier and Springer Verlag, who are able to purchase stables of specialized journals and to profit from expensive subscriptions placed by research institutions and libraries, rather than individuals. In the 1980s and 1990s, the reduction of library budgets and ceaseless growth of the printed journal literature precipitated a crisis. Computer technology and the Internet led to innovations such as online refereed publications, introduced by the *Online Journal of Current Clinical Trials* in 1992, or informal preprint servers and ftp sites; they offer the possibility of accelerating the pace of scientific publication while challenging the role of for-profit publishers by reducing the cost of disseminating results.

Henry Lowood

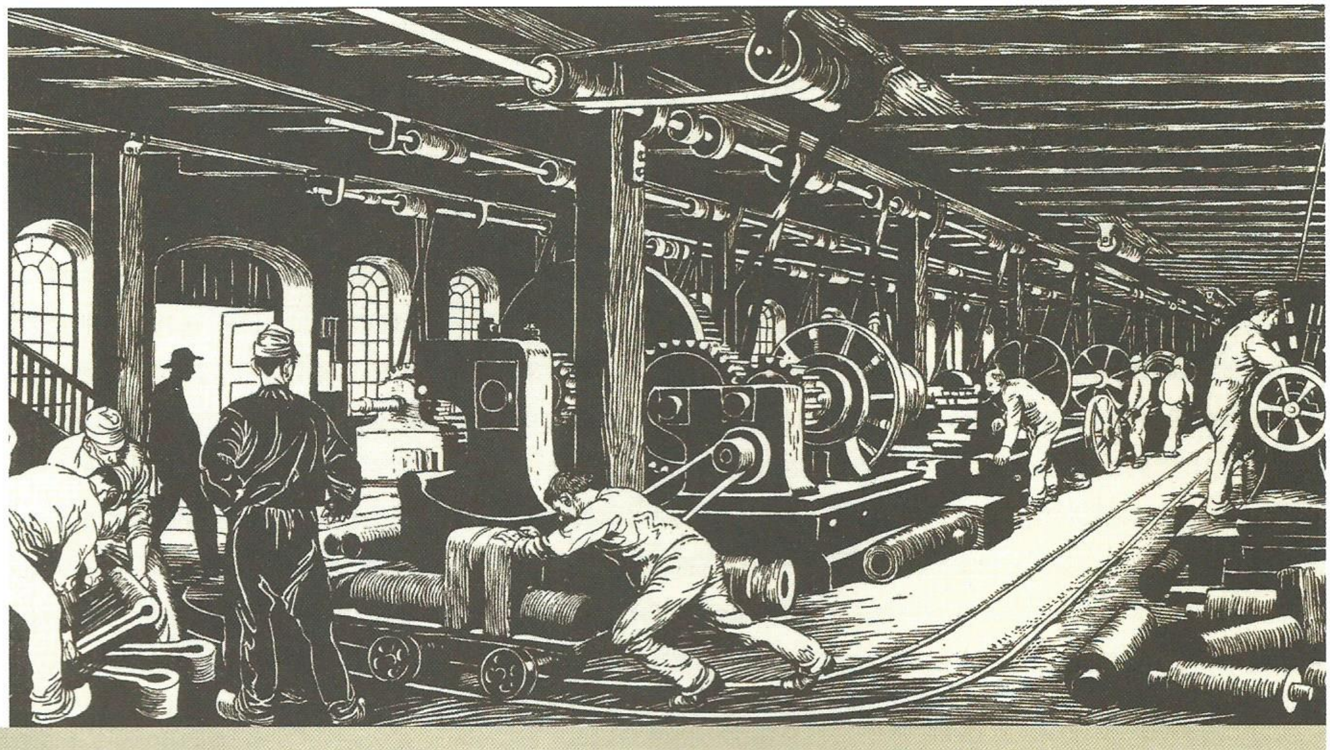
L

LABORATORY, INDUSTRIAL RESEARCH. The industrial research laboratory first appeared in commercial enterprises around 1860. Previously, research related to industrial processes took place in universities, academies, and private laboratories. Sometimes inventors set up their own enterprises with which they associated their laboratories. But after 1860, companies began establishing in-house research facilities.

The industrial research laboratory as an organizational entity has several typical features. It is generally separated from production facilities and not subject to immediate demands from production or production managers. Industrial research is a continuous activity; scientific investigations and their extension to new products become routine operations of the firm. Industrial research also features cooperation of scientists from different disciplines, engineers, technicians, and craftsmen, working in an interdisciplinary manner. Since interdisciplinary activities of people with different backgrounds and tasks make coordination and hierarchy necessary, a coordinating institution at the top of the research structure is often created for the purpose—either a central research laboratory or a responsible member of a board of directors. Those conditions of routine activity, novelty, interdisciplinarity, and coordinated hierarchy confirm a company's engagement in industrial research. The same features characterize the work carried out in industrial research laboratories.

Beginning in the late 1850s a considerable number of chemists began working in industry for iron foundries. After Henry Bessemer had announced his revolutionary process for converting iron into steel in 1856, German foundries quickly implemented his invention and employed chemists to develop and refine it, and to look for new alloys. Afred Krupp in 1863 established what was probably Germany's first industrial research laboratory at his crucible steel foundry in Essen; and in 1883 he created a second laboratory with the special mission of finding new alloys, improving existing steels, and investigating the properties of iron and steel. About one hundred foundries around Sheffield in England also set up chemical testing sites by 1900. In the United States, the Pennsylvania Railroad Company established a chemical laboratory in 1876, probably becoming the first American enterprise to do so in pursuit of technological innovations.

The emerging organic-chemical and electrical industries gave rise to a great number of industrial research laboratories from the 1870s onwards. Following the discovery in 1856 of synthetic aniline dyes derived from coal tar by William Henry Perkin and August Wilhelm von Hofmann in London, many firms were established in Britain, France, Switzerland, and Germany to develop it. These firms, synthesizing great numbers of dyes, grew rapidly. By 1880, however, advancing scientific progress, increasingly complex production processes, lawsuits over patents, and fierce

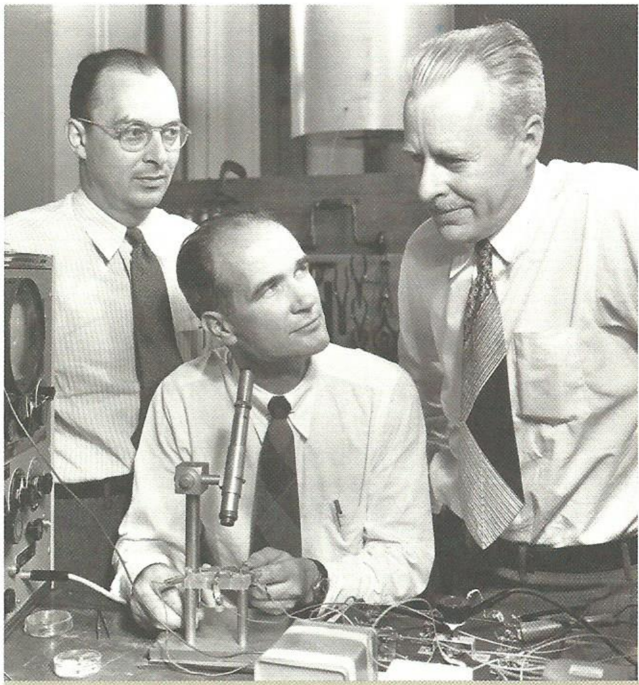


A machine hall in the Krupp works, Essen, Germany, in 1911 competition had driven many European companies out of business. Apart from a handful of British enterprises, some ten German firms continued to grow and provided 80 to 90 percent of the world production of synthetic dyes by 1913. All the surviving companies had developed particularly strong industrial research laboratories.

The firms first sought enduring connections with university researchers to supplement and later replace the scientific knowledge of the aging company founders. Moreover, the first all-German Patent Law of 1877 made copying of other companies' inventions and production processes illegal. Companies had now to file their own patents, check their claims of novelty, screen competitors' patents, and evaluate inventions and discoveries offered to them from university professors. All these were the duties of the newly established industrial research laboratories, which emerged between 1877 and 1886 in the leading German dye companies. With rapid scientific progress in new fields like pharmaceuticals, photographic chemicals, artificial fibers, and synthetic rubber, and with a continuous stream of young chemists leaving German universities, the biggest German chemical companies—BASF, Hoechst, and Bayer—each employed around 300 chemists in their large research laboratories and testing stations by 1912.

In the United States, DuPont de Nemours started the investment in industrial research by creating research laboratories from 1902 on, after it had been threatened with antitrust suits for misusing its market power in explosives. Here, industrial research, embodied in industrial research laboratories, had the function of deliberately broadening and widening the enterprise's activities.

In the electrical industry, after the introduction of the telegraph in the 1840s and 1850s, a number of firms in the United States, Germany, Italy, and Britain, and some independent inventors, notably Thomas Edison, started to work on the telephone, high voltage systems, and—in the 1870s—the incandescent light bulb. Rapid scientific and technical progress, competition for market domination influenced by national patent laws and corporate acquisitions, and, in the case of Siemens, the death of the company founder and main inventor (Ernst Werner von Siemens), prompted Siemens and Halske (Germany), General Electric (United States), and Philips (Netherlands) to set up research laboratories around 1900. They were to safeguard a constant stream of marketable new inventions and technologies. Their main activity in the first years centered on the incandescent light and lighting technologies. But with the arrival of the telephone, X rays, and new theories in physics, the scope of the research laboratories in the electrical industries widened to include vacuum tubes and X-ray machinery, and then, more generally, to encompass theoretical physics, physical chemistry, chemistry, acoustics, and mechanical technologies. Inspired by the success of others, the American Telegraph and Telephone Co. (AT&T) and Eastman Kodak (photographic equipment) also began to pursue industrial research in newly created laboratories. Despite different aims and business strategies, at the onset of World War I most large industrial enterprises in the United States, Great Britain, and Germany had departments for pursuing industrial research. Usually a centralized main laboratory directed several dispersed laboratories and testing stations while maintaining close long-term relationships with nearby universities.


Left to right, John Bardeen (1908–1991), William Shockley (1910–1989), and Walter Brattain (1902–1987) shared the Nobel Prize for Physics in 1956 for their invention of the transistor.

Drawing on war profits, a return to peacetime conditions, and a postwar economic boom, the years from 1919 to 1926 saw unprecedented growth in the number of new industrial research laboratories and the expansion of existing ones. Also, as companies grew during the war years and mergers became common, huge industrial complexes with several thousands of workers and large research facilities were established. By 1925, AT&T employed about 3,600 staff members in their "Bell Laboratories," a company it set up for the sole purpose of pursuing industrial research. The same year DuPont had a research staff of around 300 in the same year, which rose to about 700 by 1930. In automobiles, General Motors created probably the largest infrastructure for research and development. In Europe, the biggest spender on research and development was I. G. Farben, a chemical trust stemming from the merger of six German dye companies (including Bayer, BASF, and Hoechst) in 1925; it employed about 1,100 research chemists in at least sixty laboratories by 1930. Imperial Chemical Industries (ICI) in Britain, which also resulted from a merger of six chemical companies, had a research staff of around 400 chemists. In other sectors such as textiles and branded goods, British companies saw great investment in industrial research in the interwar years. In the electrical industries, Siemens and Halske employed roughly 900 chemists, physicists, and engineers in more than seventy laboratories. By 1934 Philips had a corps of 370 researchers. In steel, Germany was the home of probably the biggest industrial enterprise of the interwar years, the Vereinigte Stahlwerke AG (United Steel); it combined the research efforts of several firms, with a research staff of at least 400 people.

During World War II, each belligerent nation made use of the knowledge, technologies, and manpower of giant industrial enterprises for their war efforts. In the United States, DuPont was heavily involved in the Manhattan Project leading to the atomic bomb; in Britain, ICI also participated in a nuclear power project. In Germany, I. G. Farben supplied synthetic fuel and rubber for the war effort. All required substantial investment in science and technology to produce nuclear power, radar, antibiotics, jet engines, and early computers. The Cold War resulted in a continuation of large research efforts by both government and industry. Many companies established new industrial research laboratories.

The organization and management of industrial research laboratories have changed over time. Their number, location, administration, and coordination altered frequently as companies grew, diversified, closed, or sold production lines, or merged with other firms. Some companies found it useful to centralize all research efforts in one big department for research and development; others continued to decentralize research along product lines.

A typical modern industrial research laboratory has a managing director, group leaders, team heads, and scientists. The director reports to the company's board. An experienced scientist supervises the laboratory work of interdisciplinary groups of scientists and engineers. A large and diversified company may maintain many testing and investigating stations organized along the companies' different lines. But only the centralized, main industrial research laboratory with direct access to a company's top management enjoys the status of the scientific and technological heart of the enterprise.

Companies have tried various means of financing their industrial research laboratories. Until World War II, the divisions at Siemens had to pay for scientific investigations and tests done by its main industrial research laboratory, while DuPont allowed their laboratories to spend substantial amounts before evaluating their output. In contrast, Bayer and BASF for many decades permitted their laboratories, which produced new inventions and discoveries regularly, to function without regular evaluation. Researchers in testing stations could not choose their projects, whereas outstanding scientists in the centralized main laboratory might enjoy great freedom in deciding their agendas. Sometimes, large enterprises distanced their creative scientists from the immediate concerns of manufacturing by founding new companies or divisions only for the purpose of conducting industrial research, as AT&T did with Bell Laboratories in 1925 and Vereinigte Stahlwerke AG did with a new subsidiary in 1926. IBM located research divisions in a foreign country (Zurich, Switzerland) to safeguard academic freedom and benefit from the stimulation of a famous nearby technical university. Some companies, like DuPont during the 1930s, allowed fundamental research in their laboratories but abandoned the initiative when it gave no greater returns than earlier approaches.

Despite secrecy's importance in industrial research, especially for patentable discoveries, industrial scientists need intellectual exchange with colleagues and ways to discuss their theories and inventions. Beginning in the 1920s, after decades of secrecy, many enterprises set up their own journals to publish recent results or allowed their researchers to publish freely in academic journals. This relaxation aided recruitment of young scientists since they did not have to abandon academic standards and ambitions on entering industrial research laboratories. They could thus enhance their own and their company's reputations, build a record for transfer to a university, and earn a chance at a Nobel Prize. Winners include Irving Langmuir and Horst Störmer at Bell Laboratories in 1932 and 1998, respectively, and Gerhard Domagk at Bayer/IG Farben in 1939.

Ulrich Marsch

LAMARCKISM became a critical term in biology in the 1880s and 1890s within the debate over evolution theories that developed during the temporary eclipse of Darwinism. Given the time and context, Lamarckism, "neo-Lamarckism" (introduced by the American entomologist Alpheus Packard in 1884), and "neo-Lamarckian" (attached to the doctrines of some evolutionists active around 1900) had little to do with the theory of evolution advanced by Jean Baptiste de Lamarck almost a century earlier.

In the later context, Lamarckism designated above all the doctrines that characteristics acquired through use during the life of an organism could be transmitted to its offspring and that the environment played a direct role in the modification of living beings. Many regarded the "Lamarckian" inheritance of acquired characters as an appropriate complement, or even a necessary alternative, to Charles Darwin's notion of natural selection, which seemed unable to sustain the broad evolutionary theory and world-view that Darwin himself had advocated. The experimental evidence brought to support the inheritance of acquired characters by authors like Charles-Édouard Brown-Séquard, Paul Kammerer, Ivan Pavlov, and William McDougall, however, proved insubstantial, and the notion fell by the wayside after the severe criticism of August Weismann.

"Lamarckism" as used in biology today retains its late-nineteenth-century significance. It also evokes memories of the Lysenko affair, the dramatic confrontation in the 1930s and 1940s between a Soviet version of the doctrine of the inheritance of acquired characters, supported by Stalin's head biologist and agriculturalist Trofim Denisovich Lysenko, and Western, neo-Darwinian geneticists.

In recent decades historians of biology have unearthed evidence revealing other important, but relatively unknown chapters in the history of Lamarckism. It is now agreed that Lamarck's own works and ideas circulated more widely than previously suspected in several European countries before the publication of Darwin's *Origin of Species* in 1859. Thus, Lamarck's important legacy, and the controversial reception accorded to it in scientific and popular circles from the 1830s through the 1850s, merged in depth with the assessments of Darwin's own work. Darwin engaged in frequent dialogue with Lamarck's views and concepts while refining his own theory and presentation strategies, and subscribed to the then-popular notion of use-inheritance. Many who joined in support of evolution after 1859, including prominent defenders of Darwin's like Thomas Henry Huxley and Ernst Haeckel, and successful propagandists of evolutionism like Herbert Spencer endorsed Lamarckian, rather than properly Darwinian views. The histories of Lamarckism and Darwinism appear now more closely intertwined than was allowed by mid-twentieth-century biologists in the wake of the triumphs of the neo-Darwinian theory of evolution.

Giuliano Pancaldi

LASER AND MASER. MASERs (microwave amplification by stimulated emission of radiation) produce coherent microwave radiation with very low noise. LASERs (light amplification by stimulated emission of radiation) emit infrared-visible radiation of very high coherence. Although the idea of using stimulated emission to produce coherent radiation dates from the 1930s, the first maser, built by Charles Hard Townes at Columbia University, did not materialize until 1954. The basic idea was that if more particles of a medium can be placed in an excited rather than in an unexcited state, then a radiation interacting with the particles is amplified rather than absorbed because stimulated emission prevails over the absorption. The presence of a resonant cavity enhances the interaction of the particles with the radiation and allows the formation of an electromagnetic vibratory mode.

In his first maser, Townes used a microwave transition at 23.870 GHz (= 1.25 cm) in ammonia molecules. He employed a microwave cavity with an inverted population obtained by using a quadrupole electric field to separate the excited ammonia molecules from the unexcited ammonia molecules in a beam emerging from an oven. The excited ammonia molecules enter a cavity capable of resonating at around 1.25 cm. Here they may amplify a low signal at the resonant frequency or, if sufficiently plentiful, may generate a signal. Nicolai Gennadievich Basov and Aleksandr Mikhailovich Prokhorov in Moscow arrived at the same idea as Townes at about the same time. They wanted to improve the characteristics of microwave spectroscopes. They had noticed that a medium with an inverted population had a stronger signal to noise ratio than a normal medium.

The first ammonia maser produced very monochromatic radiation with extremely low noise. In 1956, Nicolaas Bloembergen pointed out that solid state masers might be tuned and suggested a system whose energy levels depend on the strength of an imposed magnetic field, so as to permit tuning over a considerable frequency range. The system was soon put into operation by H. E. Derrick Scovil, George Feher, and Harold Seidel at Bell Telephone Laboratories.

Although the maser represented the first application of stimulated emission, and a revolutionary way to consider microwave sources, it did not have a dramatic technological application because less expensive, smaller, and simpler semiconductor devices also could emit or amplify microwave radiation with very low noise. However, Arno Penzias and Robert Wilson used a maser when they discovered the black-body cosmic background.

Lasers extend the use of stimulated emission into the visible and infrared. Townes and Arthur Schawlow gave the first thorough discussion of their operation and properties in 1958. Two years later Theodore Harold Maiman developed the first working laser by placing a rod of ruby in the center of a helical flash lamp. The two end faces of the rod were parallel to each other and silvered so as to create an optical cavity. Pulsed radiation at 6943 Å (0.69 μm) traveling along the axis of the rod was obtained by pumping with light from the flash lamp.

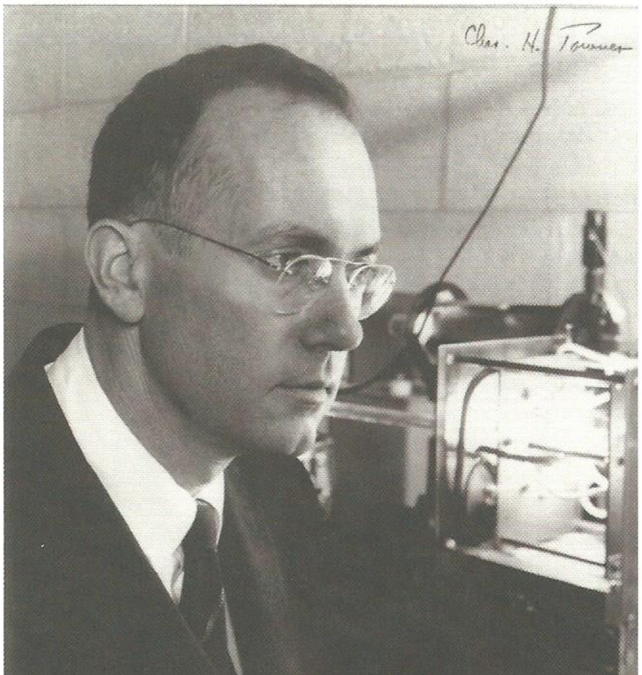
Soon Ali Javan and his associates at Bell Labs developed the first continuous gas laser utilizing a mixture of helium and neon. They obtained several inverted levels in neon by collision with helium atoms excited in a radiofrequency discharge. This laser emitted continuously at 3.95 μm, 1.1 μm, or 0.63 μm. It appeared that almost every substance can lase (serve as the medium of a laser). Helium-neon and ruby lasers were joined by neodymium lasers, which emit usually pulsed radiation of moderate coherence and high power at 1.06 μm, tunable lasers operable both continuously or with very short pulses, and tiny diode lasers stimulated directly by an electric current. The market now offers a hundred different lasers, some of which emit pulses as short as a few femtoseconds.

Even before lasers became practical, their possible applications were discussed. The military dreamed of secure communication channels, radar with great resolution, death rays to destroy enemy targets, and so on. Many applications of lasers have been found in medicine, chemistry, and spectroscopy. Today, lasers read and write compact discs, control mechanical processing and measurements, and send signals down optical fibers. Nonlinear optics was born with lasers. And in physics itself, lasers have been used to demonstrate Bose-Einstein condensation, the movement of molecules during chemical reactions, and other exotic phenomena. Lasers also had a profound influence on quantum mechanics with the development of quantum optics and the creation of coherent and nonclassical states.

Mario Bertolotti

LATIN AMERICA. The European invasion of the Americas produced a knowledge holocaust. We know little or nothing about the local institutions and artifacts that were destroyed. We eat tomatoes, corn, beans, and potatoes without understanding how they were developed. We have limited knowledge about the ways in which the indigenous peoples of what is now referred to as Latin America came to have zero, decimal positional numerical systems, books, accurate calendars, and an accounting for the motions of Venus. Although the pre-Columbian world possessed a rich network of knowledge-producing institutions, it would be anachronistic to call this knowledge science in the modern sense. The conquest, which brought with it the Inquisition and later legalized slavery, also brought conquerors who rejected "unscientific" knowledge.

The colonial period (roughly 1500 to 1800) saw some investigations of natural knowledge and some relevant institutional development. Gonzalo Fernández de Oviedo wrote his *Historia Natural y General de las Indias* describing the flora, fauna, and peoples known to the Spanish at that time. The Spanish founded institutions such as Cordoba University in Argentina in 1613. (The Portuguese did not create institutions at this level.) The region continued to draw European naturalists. Pehr Löfling, a disciple of Linnaeus, described the Orinoco flora. José Celestino Bruno Mutis, a Spaniard established in Colombia, continued Löfling's work. Mutis mobilized intellectuals in Nueva Granada in an Expedición Botanica. His disciples, Clement Ruiz Pabon and Juan José d'Elhuyar, visited Sweden in 1781.



Charles Townes (born 1915), inventor of the MASER, forerunner of the LASER

José Bonifácio de Andrada e Silva, a Brazilian elected to the Portuguese Academy of Sciences, worked in Europe from 1790 to 1799. Andrada e Silva carried Antoine-Laurent Lavoisier's ideas to Scandinavia. There he collected some 3500 minerals and fossils, which today are housed in the Brazilian Imperial Collection, Petrópolis. For a while he held the chair of metallurgy at Coimbra in Portugal. After Brazil became independent from Portugal in 1821, Andrada e Silva struggled to end slavery. Failing, he moved to France in 1823 and returned to science. Like Andrade e Silva, the naturalist Alexander von Humboldt had an interest in mineralogy. He stayed in Caracas in 1799 and 1800 and collected materials in Cuba, Mexico, Bolivia, Colombia, Ecuador, and Peru. He expanded the horizons of European scholars with his descriptions of the New World, in which he did not always fully acknowledge Mutis's contributions.

In the half-century following the independence of Latin American nations from Spain and Portugal (roughly 1820 to 1870), several important Europeans and North American naturalists visited the region. Alfred Russel Wallace went to the Amazon; Charles Darwin visited many parts of South America including Argentina and the Galapagos Islands; Eugenio Warming and Peter Wilhelm Lund carried out biological and paleontological studies in Lagoa Santa, central Brazil. Some of the stream of visitors stayed and contributed to the scientific and institutional growth of Latin America. An outstanding example, Fritz Müller, a Ph.D. from the University of Berlin and an M.D. from the University of Greifswald, moved to Blumenau in Brazil in 1852. He corresponded with Louis Agassiz, Max Schultze, Ernst Haeckel, and Charles Darwin. His book *Für Darwin* appeared in Leipzig in 1864 and, in an augmented English version, *Facts and Arguments for Darwin,* in London in 1869. His work on the evolution of Brazilian crustaceans provided solid support for Darwin's theory and won Müller an honorary doctorate from the University of Bonn. Nearly all of Müller's 248 published scientific works were written in Brazil.

While positivism did not receive support from European natural scientists, it had a profound impact in Latin America. Auguste Comte, positivism's founder, maintained that humanity evolved according to a law of the three stages. The most primitive of these, the theological stage, was characterized by a belief in supernatural forces. Positivists regarded Catholic Latin American countries as theological states dependent intellectually on Europe. In Argentina, President Domingo Faustino Sarmiento, who greatly contributed to the country's development, believed—under the inspiration of Comte's theory of stages modified by a Romantic evolutionary theory—that civilization was urban and European. The doctrine made it difficult for Argentinian scientists to obtain local patronage. The director of the Buenos Aires Natural History Museum, zoologist Hermann C. C. Burmeister, refused to support Florentino Ameghino, a local genius whose biological and paleontological work was known in Europe. Europeans and North Americans occupied many important posts; Benjamin A. Gould at the Cordoba Astronomical Observatory and Emil Bose at the La Plata physics institute are examples.

In Brazil, Emperor Pedro II promoted science and letters. Nevertheless, the establishment in 1889 of a positivist republic by the military left the country without universities. Military schools taught from positivist writings and fostered applied research. The Campinas Agricultural Institute, the Butantã Biological Institute, and the Institute for Technological Research (IPT) exemplify the sorts of institutions then founded. The IPT, a test center for industry and civil engineering, was founded in 1899 by Antonio Francisco Paula Souza, one of the first ministers of the Brazilian positivist republic. Medical science made outstanding advances. Oswaldo Cruz, founder of Brazilian experimental medicine, eradicated yellow fever, bubonic plague, and smallpox from Rio de Janeiro despite positivist opposition. One of the major biomedical research institutions of Latin America, the Oswaldo Cruz Foundation, bears his name.

After 1914, the influence of positivism declined throughout Latin America. This decline had many benefits. Distorting Comte's work and accepting it as absolute truth, the Latin American positivists not only had opposed the teaching of most post-Newtonian physics, including the concept of electromagnetic field and non-Euclidean geometry, but also governmental engagement in the institutional development of science and education, including the creation of universities. Their position in technical and military schools made it all the more difficult for scientific advance.

As a new way of thinking emerged, Argentine science flourished. With a per capita income greater than that of Italy or Sweden, Argentina attracted the European powers. Both the French and the Spanish promoted their own institutes and lectures in Argentina. The Germans supported physics at Emil Bose's La Plata physics institute. Bose hired Einstein's former assistant Johann Laub, the engineer Konrad Simons, and some brilliant Argentineans. Richard Gans, who had studied with Ferdinand Braun at Strasbourg, succeeded Bose in 1911. Niels Bohr noticed Gans's application of H. A. Lorentz's theory of magnetic fields to free electrons. Between 1925 and 1945 Gans taught in Germany, which gave Argentineans, including Gans's student Enrique Gaviola, who received his doctorate from Berlin in 1926, opportunities to study there. Unfortunately this flowering of Argentinean science did not last.

In Brazil, the antipositivist reaction resulted in the foundation of the Brazilian Academy of Sciences (ABC) in May 1916, supported by the Associação Brasileira de Educação (Brazilian Association for Education) and the Instituto Franco-Brasileiro de Alta Cultura (French-Brazilian Institute for Advanced Studies). ABC had its own periodical, renamed in 1929 the *Anais da Academia Brasileira de Ciências.* Its leaders included naval officer Álvaro Alberto da Mota e Silva, its president from 1935 to 1937. The opposition to positivism became public during Einstein's visit in 1925 on his way to Argentina. At Sobral, in the northeast of Brazil, the expedition coordinated by Arthur Eddington photographed the eclipse of 1919, validating the general theory of relativity. The Brazilian positivists had opposed Einstein's ideas in newspaper articles but suffered ridicule after the eclipse findings became known.

Brazilian and American agriculture prospered from international connections. In 1925 Iwar Beck-man from Sweden developed the wheat hybrid Frontana at the Alfredo Chaves experimental station in Vereanópolis, Rio Grande do Sul. This variety saved North American wheat growers after the problems caused by leaf rust in the 1940s and 1950s.

In the 1930s, after a failed revolution against the central government, the São Paulo elite created the Universidade de São Paulo (USP) as an instrument for social and economic development. A number of European researchers, including Fernand Braudel and Claude Lévi-Strauss, became USP professors. Physicist Gleb Wataghin, a Ph.D. from Turin University, also joined USP. He discovered cosmic-ray showers and developed the theory of the multiple production of cosmic rays. He trained a number of students and his group actively cooperated with Arthur Holly Compton during his cosmic-ray expedition in the 1930s.

Mexicans also participated in Compton's project. Manuel Sandoval Vallarta, who graduated from MIT in 1921 and joined its faculty, became interested in Compton's discovery of charged particles in cosmic rays. Vallarta demonstrated experimentally Oliver Heaviside's formulas for the electromagnetic propagation in conductors as well as his operational calculus.

Vallarta and his colleague at MIT, Georges Lemaître, followed up Comptons's experimental results on the effect of the earth's magnetic field on cosmic rays. Lemaître had suggested that the universe originated from one primitive atom or "cosmic egg." His work with Vallarta, which concluded that charged particles made one component of primary cosmic rays, supported the cosmic-egg theory. In 1943 Vallarta became professor of physics at the National Autonomous University of Mexico (UNAM). He had a profound influence on Mexican physics. His students include Alfredo Baños, Carlos Graef Fernandez, Luis Enrique Erro, and Marcos Moshinsky. Outside Mexico, Vallarta's most famous student was Richard Feynman.

Between 1945 and 1990, science and the state had a love-hate relationship in Latin America. On several occasions, states exiled their brightest while trying to foster science that might aid development. Under the regime of President Juan Perón, Argentina missed many opportunities to build. Immediately after World War II, Gaviola planned an atomic research institute and invited Werner Heisenberg, who accepted but never came. The international press, fearing atomic weapons in the hands of a totalitarian regime, attacked the plan. When the United States announced at the United Nations Atomic Energy Commission (UNAEC) that it was ready to retaliate against what it considered "illegal" atomic programs, and a U.S. Air Force B-29 squadron flew over Montevideo, the Perón regime dropped Gaviola's project.

This incident, combined with conflicts between Perón and the universities, made the Richter adventure possible. Austrian chemist Ronald Richter arrived in Argentina in August 1948 and convinced Perón to build laboratories at Bariloche. In March 1951, Perón announced that Richter had discovered how to control nuclear fusion. Ridiculed by the scientific community, Perón ended the project in November 1952. The nuclear field, under the leadership of Gaviola, Jorge Sabato, and José Antonio Balseiro, flourished. The Atucha 1 nuclear reactor went critical in 1967. Argentina has sold nuclear knowledge to Peru, Algeria, Turkey, Iran, and Australia.

The sort of support given nuclear physics did not recur in other areas of knowledge. Normally scientists and professors worked under pressure and even persecution. Expelled from his university, the Argentinian physiologist Bernardo Alberto Houssay went on to receive a Nobel Prize in 1947. By the mid-1970s, the universities were completely dysfunctional, 547,000 Argentineans had left the country, and an unknown number of students had disappeared.

In Brazil, constant tension existed between the government and the scientists even though both sides believed that science should contribute to development. Gradually, thanks to the Brazilian National Research Council (CNPq), research centers such as the Brazilian Center for Physics Research (CBPF) were founded according to a plan outlined at the ABC meetings in 1945. Alvaro Alberto described the requirements for the atomic age: research, mineral prospecting, and proper industrial facilities for isotope production and assembly of instruments. The ABC requested that the government invest in research centers, send Brazilians abroad for training, and invite foreign scientists to visit Brazil. Nuclear relations between Brazil and the United States turned on Brazil's possession of monazite, a major source of thorium, cerium, and other rare earth metals and compounds. Brazil wanted to exchange monazite for nuclear technology. The United States responded with a systematic smuggling of the ore.

Getúlio Vargas, elected president in 1951, supported the Brazilian program of science for development. Like President Truman, Vargas considered nuclear energy an important component of industrialization. Nevertheless, the United States opposed the Brazilian program. Brazil started an independent program that included a secret agreement with occupied Germany. It collapsed in 1955, but the institutions it created became the basis of Brazilian scientific growth. In 1975, a new agreement was reached between Brazil and Germany, but Germany failed at transferring nuclear technology to Brazil.

After 1955, international cooperation in physics grew. One example is the partnership between Nordita, the Nordic Institute for Theoretical Physics headed by Bohr, and the Porto Alegre Physics Institute. In the late 1950s and early 1960s, Theodor A. J. Maris and Gerhard Jacob (president of CNPq in the 1990s) visited Nordita. Their leadership transformed Porto Alegre into a center for research on the Mössbauer effect and gamma ray correlation, two major research methods in nuclear physics. The application of these methods to solid state physics catapulted graduates from Porto Alegre into leading positions elsewhere. Other Latin Americans visited Nordita, for instance Argentinean solid-state physicist Leo Falicov, a link between Latin America and Berkeley. His best-known Porto Alegre student, Cylon E. T. Gonçalves da Silva, founded the Brazilian synchrocyclotron accelerator at Campinas.

In Mexico, President Aleman heeded the warning of Vallarta, Graef Fernandez, and others. In August 1945 he made science-for-development one of his main policies. In 1949, Vallarta moved to Mexico as full professor. Thanks to many like him, Mexico developed a unique nuclear policy that reflected views popular at the time. Many Mexicans believed that the United States's atomic monopoly increased injustice, poverty, and violation of rights. This perception led to the Tlatelolco Treaty of 1994, which renounced all military nuclear programs. Science-for-development became the enduring center of Mexican research, notably in agriculture. Supported by the Rockefeller Foundation and the Mexican Ministry of Agriculture, CIMMYT, the International Maize and Wheat Improvement Center, produced high-yield corn varieties. The Green Revolution, despite downplaying local varieties and increasing petroleum dependency, did achieve its goal of increasing global food production. Institutions modeled after CIMMYT were created in other parts of the world.

The difficulties of practicing science on the periphery may be indicated by the nominations of Latin American scientists for Nobel Prizes. In the 1920s and 1930s the Brazilian Carlos Chagas was nominated four times for the prize in medicine. In 1909 he discovered Tripanossomiase americana, identifying the disease parasite and vector. Known today as Chagas disease, it plagues over twenty million persons in at least eighteen countries. International recognition of his achievement would have translated into visibility and power at home. Envious, Afrânio Peixoto, rector of Rio de Janeiro University, mobilized attacks on Chagas. At the National Academy of Medicine, Chagas faced criticism from influential persons, and his work was not incorporated into medical education. In 1912, he received the Schaudinn Prize, awarded by the Hamburg Institute for Tropical Diseases. Yet when the Nobel Prize secretariat approached Brazilian authorities about the nomination, neither the medical community nor the politicians recommended Chagas. Other potential Brazilian Nobel candidates were Leite Lopes and Cesar Lattes.

In 1947, Bernardo Houssay was awarded the Nobel Prize for medicine (along with Carl Ferdinand and Gerty Cori). As a student, Houssay had developed a method to investigate pituitary gland hormones. He became professor of physiology in 1909, a year before receiving his degree with an award-winning dissertation. In 1943, the Peronists, in a crackdown of potential opposition, evicted him from the University of Buenos Aires. Supported by the Rockefeller Foundation and a local entrepreneur, Juan Bautista Sauberan, Houssay founded the Institute of Experimental Biology and Medicine. He continued his research on the pituitary, insulin, and diabetes; trained over 250 doctoral students; and published over two thousand scientific papers.

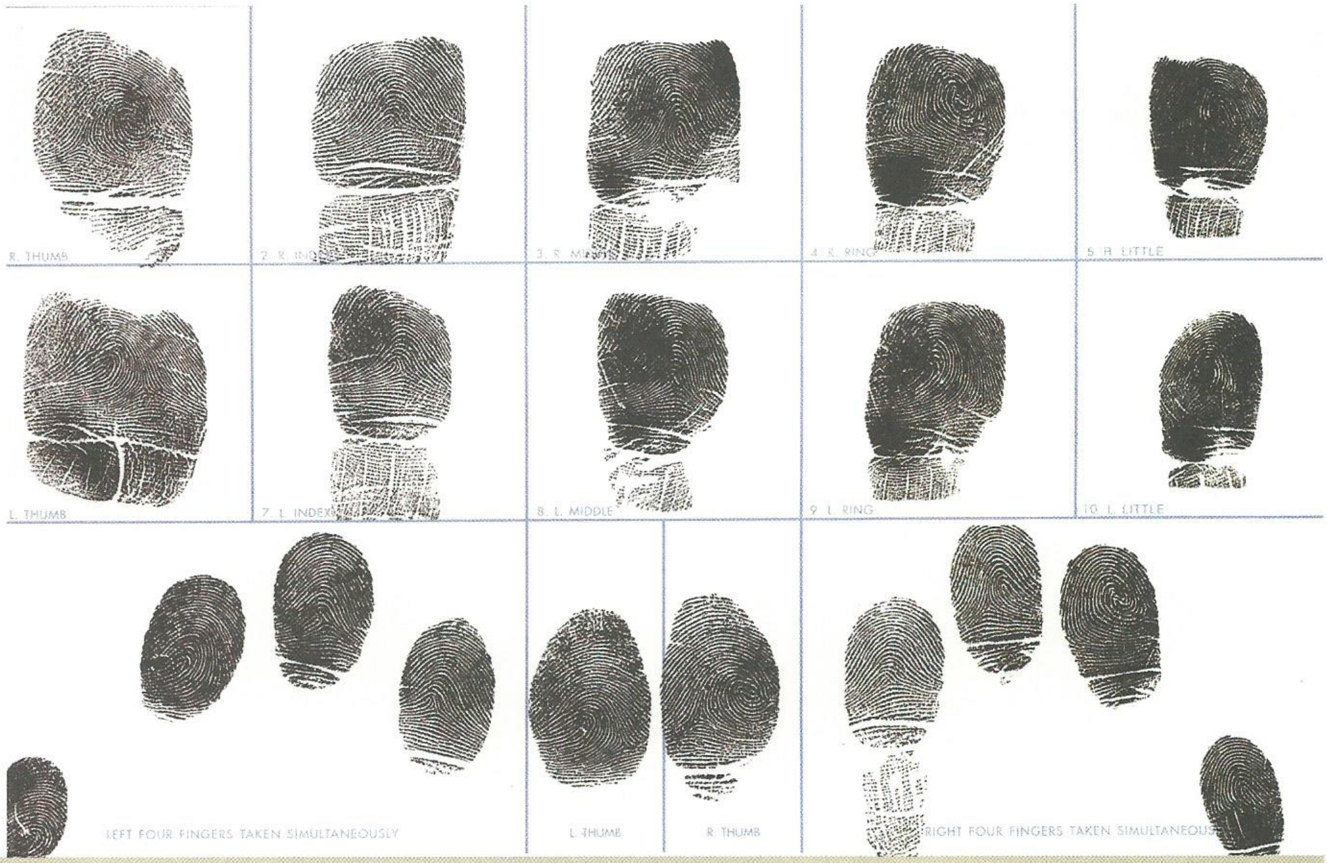
In 1970, Luis Federico Leloir from the Institute for Biochemical Research, Buenos Aires, received a Nobel Prize for his research on sugar nucleotides. Leloir took his M.D. in Buenos Aires in 1932 and worked in Houssay's institute until interrupted by Peronism. He moved to the Corises' biochemical laboratory at Washington University and then to David Green's experimental medicine institute at Columbia. On his return to Argentina, Leloir, like Houssay before him, founded his own institution, the Fundación Campomar (1947). The award of the Nobel Prize sheltered him from the vicissitudes of politics and military persecution. Leloir is a role model for Argentinean scientists.

In 1984, Niels Jerne, Georges Köhler, and Cesar Milstein shared the Nobel Prize for medicine or Physiology for their work on the immune system and the production of monoclonal antibodies. Born at Bahia Blanca, Argentina, Milstein was a graduate in chemistry from the University of Buenos Aires. In 1952, he completed a Ph.D. on aldehyde dehydrogenase at the Institute of Biological Chemistry. With a fellowship from the British Council, he received a second doctorate for work on enzyme active sites with Frederick Sanger at Cambridge in 1960. In 1961, Milstein became the head of the Division of Molecular Biology at the National Institute of Microbiology, Buenos Aires. In 1963 he resigned when the military began to persecute intellectuals and scientists. Milstein returned to Cambridge and to a Nobel Prize trajectory.

As can be seen from these cases, the lack of recognition for Latin American science can have as much to do with internal factors as with external ones. Historians of science, most but not all of them from Latin America, are trying to record the rich history of which only a few examples from Mexico, Brazil, and Argentina have been presented here. Further information about these and many other cases may be found in *QUIPU,* the main Latin American journal for the history of science, founded in 1984.

Regis Cabral

LAW AND SCIENCE are central establishments of modern Western culture. Law directs our action in the world; science our knowledge of the world. Scientific knowledge and techniques have played an ever-increasing role in the spreading of justice in modern society. Institutions of the law have helped to clarify the character of legitimate scientific knowl-



An FBI form completed with all ten fingerprints edge and practices, and to readjust the social and institutional relations that their application required.

The law was a major patron of nineteenth-century science. Men of science served as representatives, consultants, and witnesses for the courts and the interested parties in the rising tide of litigation on matters of energy (first gas and oil, and later electricity), environment (pollution and contamination), public health (food and drug adulteration, water supply, sewage treatment), transportation, communication, mining, industry, agriculture, insurance, patents, and, of course, forensics. At the beginning of the nineteenth century, forensic experts employed only basic microscopy and toxicology; by its end, they detected stains and forgeries using infrared and ultraviolet light, differentiated human from animal blood, identified people by body shape, traced minute quantities of inorganic substances by their line spectra, reconstructed important characteristics of a corpse from partial clusters of its bones, and photographed the insides of items with X rays.

Early in the twentieth century, experts learned to identify people by their fingerprints and firearms by their ballistic prints, and to determine genetic relations by blood groups. By the end of the century, toxicology broadened to evaluate occupational exposures, public health hazards, and toxic wastes. Epidemiology grew from the study of disease transmission to accidents, birth defects, and mental illnesses. X-ray technology was joined by other medical imaging techniques, such as computerized tomography (CT), positron emission tomography (PET), and magnetic resonance imaging (MRI). Electron microscopes detected the tiniest clues of crime, and molecular biology identified people and determined their genetic relations. The twentieth century also saw a growing involvement of social scientists expert on the qualities of parenting, the causes of violence, and the validity of eyewitness testimony and repressed memories. Social scientists likewise provided statistical and methodological arguments vital for the resolution of disputes such as antitrust litigation and employment discrimination.

The criminal justice system was but one of the modes of interaction of science and law. During the nineteenth century patent law became a major mediator between the producers of scientific knowledge and those who adapted it to the various wants of society. Late in the century, the legal domain of regulation evolved to control the risks scientific knowledge and its technological products created for public safety and the environment. The twentieth century saw the continual intensification of this regulatory effort and the growth of governmental agencies to protect public health, the environment, workers, and consumers. Meanwhile, private tort law evolved to provide individuals with a way to seek compensation for scientific-technological breakdowns. In recent decades, massive legal controversies in which hundreds of thousands of claimants sought compensation for industrial accidents, polluted environments, workplace hazards, and defective products, have clogged the courts.

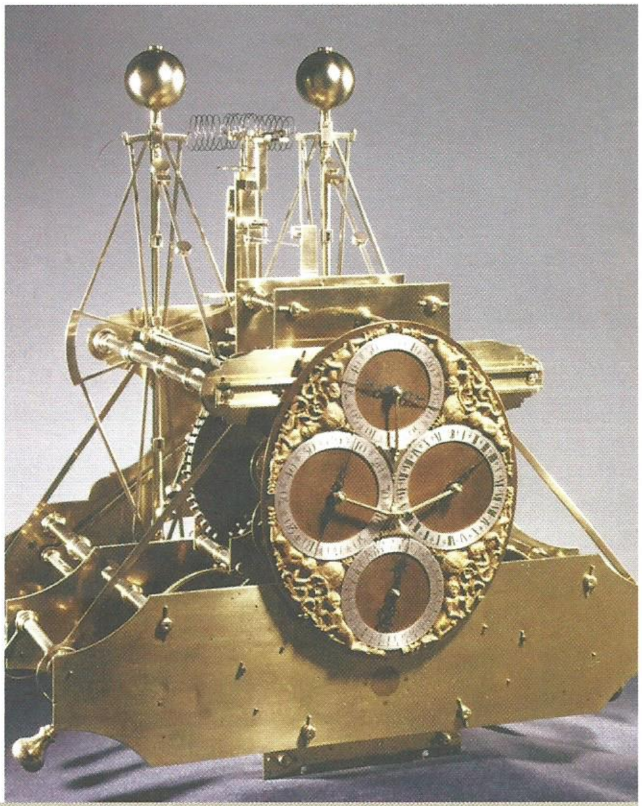
Twentieth-century developments in medical research, genetics, molecular biology, and their associated biotechnologies presented new legal challenges. Expanded options for contraception and abortion created one set of legal conflicts within changing public expectations about women's sexuality and liberty and the legal rights of the human fetus. Reproductive technologies such as artificial insemination, in vitro fertilization, and embryo implantation created a second set of legal conflicts for family and parenthood. Dramatic advances in surgery, organ transplantation, drug therapy, and resuscitation created a third set of legal conflicts around the questions of patients' rights and the responsibilities of the state and the medical community. Public fears and distrust of biotechnology created a fourth set of legal disputes, which have resulted more often than not in decisions favoring the interests of science and industry. The most notable instances were the patentability of genetically engineered life forms in the 1980s and their release into the environment.

The law typically refrained from intruding upon the practice, management, and dissemination of basic science. The processes of peer review, funding, teaching, publication, and laboratory and research administration ordinarily remained outside the purview of the courts. Still, in the late twentieth century courts were asked to clarify the boundaries of acceptable behavior by scientists and scientific institutions, and to adjudicate claims of fraud, misrepresentation, and misappropriation of research results; bias in peer review; and mistreatment of experimental subjects. A second avenue by which the courts became involved in the activities of basic science was litigation arising from moral and religious opposition to the purposes of modern science and challenges to the privileged status the scientific enterprise enjoys in modern culture. The attacks on nuclear energy and biotechnology by social critics are a case in point. So are the assaults on science by animal rights activists, conservationists, antiabortion groups, and creationists. In some of these cases the law cast its regulatory net over scientific practices. On the whole, though, the law continued to defer to science and has been reluctant to participate in assaults upon the scientific enterprise, or to adjudicate between science and other belief systems in ways that could obstruct the advance of science and its values.

Tal Golan

LIGHT, SPEED OF. Several investigators tried to measure the speed of light in the seventeenth and eighteenth centuries. Galileo, or perhaps later his followers, flashed light to an assistant, but the speed was too great to measure. In 1675, the Danish astronomer Ole Rømer noticed that intervals between eclipses of Jupiter's moons are less when Jupiter and the Earth approach each other; he correctly attributed the phenomenon to the time it takes light from Jupiter to reach the Earth. Using contemporary estimates of satellite periods and distances, Roemer calculated a velocity of 214,000 kilometers per second (k/s). James Bradley's discovery of the aberration of starlight provided a second means of estimating the speed of light, since the aberration angle depends upon the ratio of the speeds of the observer and of light. If extended to the speed of light, Bradley's calculations would have produced about 264,000 k/s.

In the nineteenth century, French physicists Armand-Hippolyte-Louis Fizeau and Jean Bernard Léon Foucault made terrestrial measurements of the speed of light by passing a beam through the gaps in a rapidly spinning toothed wheel. They obtained values of 315,300 and 298,000 k/s. The American physicist Albert A. Michelson improved on their experiments by measuring the interference fringes produced by a light beam split up in his "interferometer" and made to traverse slightly different paths through it. That raised the light velocity to 299,910 k/s (1879). Next Michelson attempted to detect the expected change in the speed of light caused by its motion through the hypothetical luminiferous ether. The surprising null result of the 1887 ether-drift experiment suggested that the speed of light is constant, independent of the speed of the emitting body. This result became a crucial element in the pedagogy, and perhaps in the discov-



The Marine Timekeeper no. 1, (1735) invented and built by John Harrison (1693–1776)

ery, of Einstein's relativity theory. Subsequent measurements of the speed of light over precisely measured distances and timed electrically ended in the spurious agreement of several sets of pre-1941 measures at 299,776 k/s. Holding Michelson in awe, followers ended their searches for flaws in their experimental apparatus when their measures agreed with his. New technologies later increased the accepted speed by nearly 17 k/s, more than four times Michelson's purported 4 k/s margin of error, to 299,792.5 k/s. Newer technology, including radiotelemetry, also improved the determination of planetary distances and the astronomical unit.

Norriss S. Hetherington

LONGITUDE is the angular distance east or west of a standard meridian, the complementary coordinate to latitude (the angular distance north or south of the equator), both used in expressing geographical location. It has been important in science because of its significance for astronomical observation and because of the influence of attempts to devise a method for finding longitude when at sea.

Various standard meridians have been determined by the position of an important observatory, a large port, or a significant geographical feature such as the Canary Islands, as used by Gerardus Mercator. The international agreement of 1884 to accept the line of longitude through Greenwich as the world's prime meridian owed much to the diligent work of astronomers at the Royal Observatory, but also reflected Britain's imperial dominance and the quality of its official sea charts.

Difference in longitude amounts to difference in local time (places distant by fifteen degrees differ by one hour). The time at a distant meridian can be found in a number of ways and compared with local time determined astronomically. A lunar eclipse, for example, might be timed, and its occurrence compared with the time given in ephemerides calculated for a standard meridian, making allowance for a variety of factors such as parallax. Galileo suggested that Jupiter's four moons, which he discovered, offered a handy celestial clock, with numerous moments of coincidence with the limb of the planet and between the moons themselves. Simultaneous timing of explosions of rockets, or direct connection by geodetic survey, provided other methods in favorable circumstances.

Methods viable on land were rarely useful at sea, where the problem of finding longitude, made acute by voyages of discovery into the Atlantic and Indian Oceans, became a synonym for the impossible. Three influential methods were proposed in the sixteenth century. The chronometer method involved the apparently simple expedient of carrying a portable watch set to standard time. Suggested by Gemma Reiner (called Frisius) in 1530, much mechanical ingenuity would be required to bring timekeepers up to the level of seagoing robustness and accuracy necessary to make this method useful. The lunar-distance method, proposed by Johann Werner in 1514, involved the measurement of the moon's position with respect to certain stars, and the calculation of standard time from the measurement via tables prepared by astronomers. At this stage, the lunar theory, the stellar positions, and the seagoing instrument to make the measurement did not exist. A third method did not depend on timekeeping but on global accounts of the distribution of magnetic variation with latitude (which could be measured directly) and longitude (which could not). Martin Cortes maintained the currency of this idea through his much-translated and republished textbook, *The Arte of Navigation* (1561).

Attempts to effect these methods led to many significant developments—from the beginnings of state-sponsored observatories in Europe to the invention of the spring-regulated watch. The most famous of the rewards offered for a solution to the longitude problem—the £20,000 prize established in Britain in 1714 to be administered by a Board of Longitude—resulted in enormous interest in the problem in the eighteenth century, and eventually the completion of both the chronometer and lunar-distance methods, seen as rivals throughout their development but used in complementary ways in the navigational practices of the nineteenth century. Both Johann Tobias Meyer (posthumously), for lunar work, and John Harrison, for a chronometer, received part rewards from the Board, Harrison's being later made up to the maximum amount by the British Parliament.

Jim Bennett

LOW-TEMPERATURE PHYSICS. The field of low-temperature physics, or cryogenics, emerged in the late nineteenth century. In 1877, two researchers succeeded in liquefying oxygen independently within days of each other. Raoul-Pierre Pictet, a Swiss physicist, and Louis Paul Cailletet, a French mining engineer, both cooled oxygen gas under pressure, then rapidly expanded the volume to condense the gas. Cailletet soon reproduced the feat with nitrogen. In 1895, Carl von Linde in Germany and William Hampson in England developed a method for industrial-scale production of liquid air, which aided subsequent cryogenics research. The three leading low-temperature laboratories—at the University of Leiden (under Heike Kamerlingh Onnes), the University in Cracow (Karol Olszewski), and the Royal Institution in London james Dewar)—engaged in a race to lower temperatures and the liquefaction of hydrogen and, after its discovery on Earth in 1895, helium. In 1898, Dewar won the race for hydrogen, using a variation on Linde's technique to reach about 20° Kelvin. In 1908, Kamerlingh Onnes used liquid hydrogen to cool helium enough to condense it at low pressure, at around 5° K. The Leiden laboratory thereafter enjoyed a fifteen-year monopoly in the production of liquid helium.

The early history of cryogenics illustrates the proliferation of academic research laboratories in the late nineteenth century, and their move into fields requiring such relatively expensive apparatus. The work involved chemists, engineers, skilled glassblowers, and instrument makers as well as physicists. Kamerlingh Onnes's success with liquid helium owed as much to his ability to form a team with physical, mechanical, and chemical expertise as to his high standards of experimental precision and keen grasp of thermodynamic and electromagnetic theory.

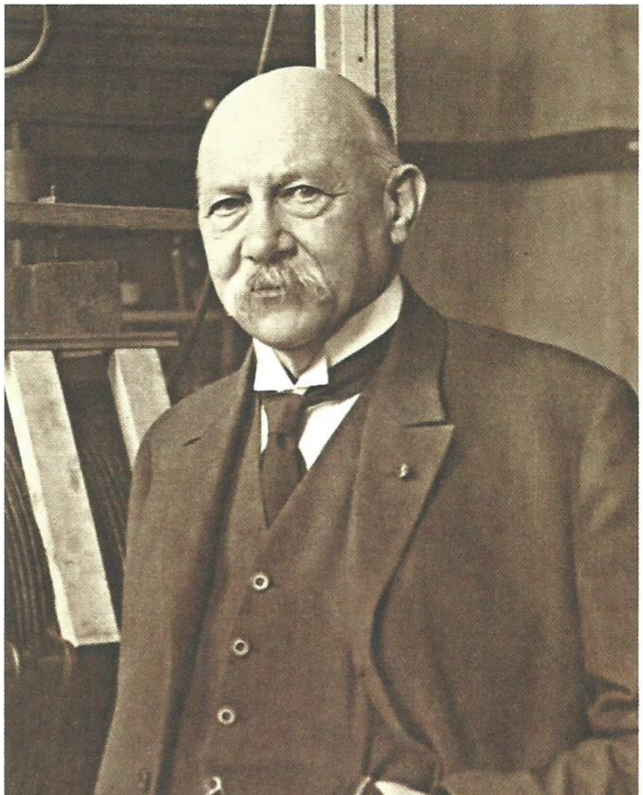
Cryogenics demonstrates the interpenetration of industry and science in the second industrial revolution—in particular, the budding refrigeration industry, which had emerged as a rival to natural ice in the late nineteenth century, especially for brewing lager beer and shipping meat to Europe from Argentina and New Zealand. Industrial uses of liquid air and its components, such as liquid oxygen for oxyacetylene blowtorches, spurred the formation of firms such as Linde Air (founded by von Linde), British Oxygen Company, and L'Air Liquide. Dewar's development of a silvered, double-walled flask with an intervening vacuum led quickly to a commercial market in thermos bottles (although Dewar failed to patent his flask). Kamerlingh Onnes had ties to Dutch industry. The industrial relevance of low-temperature research induced national governments to sponsor it in their standards laboratories such as the U.S. National Bureau of Standards and the German Physikalisch-Technische Reichsanstalt (PTR).

Academic physicists instigated their own low-temperature programs. The elucidation of specific heats at low temperatures, explored by Dewar and extended by Walther Nernst and F. A. Lindemann, provided important evidence for the fledgling quantum theory before World War I and helped establish low-temperature research as a fruitful field of physics. Pyotr Kapitsa's investigation of magnetic effects at low temperatures in Cambridge, which he continued in Moscow, and William Giauque's work on magnetic cooling and specific heats in Berkeley illustrate the spread of low-temperature physics in the 1930s. Cryogenic techniques would find application after World War II in the production of the first thermonuclear fusion weapons, in rocket propellants, and in bubble chambers for particle physics experiments. The volatile liquids and high pressures of cryogenics required elaborate safety precautions, although they did not always prevent catastrophic explosions.

Two important lines of research emerged from peculiar phenomena observed at low temperatures. In 1911, Kamerlingh Onnes and his collaborators found that electrical resistance in mercury suddenly vanished at 4° K. This "superconductivity," as Kamerlingh Onnes called it, puzzled theorists for decades. In 1933, Walther Meissner and Robert Ochsenfeld at the PTR in Berlin found that magnetic induction as well as electrical resistance disappears in a superconductor, and hence showed that superconductivity included more than its name indicated. In 1957, John Bardeen, Leon Cooper, and John Schrieffer of the University of Illinois produced a satisfactory microscopic explanation of superconductivity, based on quantum mechanical coupling of electrons with opposite spin.

Superconductivity promised spectacular technological applications in low-loss electrical power transmission and high-power superconducting electromagnets. But known materials that exhibited superconductivity proved too fragile for power transmission; and, like heat, high magnetic fields, as in electromagnets, destroy the superconductive state. Hopes for new technologies rekindled with the discovery of so-called type II superconductivity in 1961, which persevered in the presence of magnetic fields, and then flared anew with the announcement in the mid-1980s of a class of ceramic materials that stayed superconductive at temperatures up to 100° K.

The second peculiar phenomenon that stemmed from observations by Kamerlingh Onnes was a drop of density in liquid helium below about 2° K. With the spread of low-temperature physics, unexpected results with liquid helium began to accumulate, suggesting two different states of helium: normal helium I and low-temperature helium II. In 1937 and 1938 several physicists established that the viscosity as well as the density of helium II seemed to vanish, and that it could form a thin film that swept up the sides of vessels; Kapitza termed the effect "superfluidity." In 1955 Richard Feynman arrived at a microscopic theory of superfluidity based on quantization of vortices in the fluid. The theories of both superconductivity and superfluidity rely on interactions among individual particles or atoms; Pauli's exclusion principle does not apply, and Bose-Einstein statistics instead of Fermi-Dirac statistics govern the behavior. In other words, superconductivity and superfluidity are macroscopic quan-



Heike Kamerlingh Onnes (1853–1926), Dutch physicist, was the first man to liquefy helium.

tum phenomena; hence their novelty and interest, and the difficulty in accommodating them within physical theory.

Peter J. Westwick

LYSENKO AFFAIR. Lysenkoism was a doctrine of heredity espoused by the Soviet agronomist Trofim Denisovich Lysenko that contradicted modern genetics. Lysenko began propagating his views in the 1930s, gradually winning the support of many journalists, educators, administrators, and officials of the secret police. In 1940, Lysenko's most prominent opponent, the internationally known geneticist Nikolai Vavilov, was arrested; he died three years later in prison. In 1948, Lysenko won a complete victory by gaining the backing of Stalin and the Soviet government. Departments of genetics in universities and research institutes were forced to follow the new official view. Lysenko became the autocrat of Soviet biology, often casting his critics as traitors to the Soviet Union. Several thousand Soviet biologists opposing him were arrested. Not until 1965, after the fall of his supporter Nikita Khrushchev, was Lysenko finally overthrown.

Commentators in the West commonly explain Lysenko's influence by a consonance between his support for the doctrine of the inheritance of acquired characteristics and Soviet ideological desires to "create a new Soviet man." If people can inherit improvements acquired from the social environment, so the argument goes, then revolutionary changes in society can quickly result in the improvement of human beings. This explanation cannot stand. Lysenko believed in the inheritance of acquired characteristics in plants and animals, but he opposed applying his views to humans; he regarded attempts to alter human heredity as examples of bourgeois influence on science. All of Lysenko's work concerned plants and animals of agricultural value, including wheat, tomatoes, potatoes, corn, chickens, and dairy cows. His rise to prominence was linked to his efforts to aid Soviet agriculture at a time when forced collectivization had lowered productivity. None of his nostrums led to genuine improvement of agriculture. Rather, his monopoly of Soviet biology for several decades prevented the Soviet Union from receiving the agricultural benefits of modern genetics.

Lysenko's unsophisticated biological views were embodied in a vague "theory of nutrients" that assigned primary importance to the environment in the determination of heredity. He denied the existence of genes and disputed the importance of DNA. He regarded heredity as a property of the "entire organism." He claimed to have changed several species of plants into new ones by manipulating environmental conditions, claims that many biologists at the time recognized as false. Most of his methods, however, were less ambitious; for example, his attempt to accelerate the maturation of crops by soaking seeds before planting. Soviet administrators liked this approach because, if successful, it might allow harvesting before the fall frosts that plagued Soviet agriculture. Lysenko's most costly, even disastrous, biological experiments came toward the end of his career, when he caused severe damage to the dairy industry by breeding pedigreed cows with less valuable bulls, canceling the results of generations of careful animal husbandry.

China developed a Lysenkoist movement in the early phases of Mao Tse-Tung's rule. Between 1949 and 1956, a period in which Chinese leaders copied Soviet policies, Lysenkoism was the only officially sanctioned approach to genetics. Led by Luo Tianyu, a plant breeder in the Beijing area, Chinese Lysenkoism stressed populist and nativist themes, ascendant since the 1949 revolution, and won political favor more for these reasons that for any imagined contribution to agricultural technology. Mao's brief "Hundred Flowers" campaign of relative intellectual openness in 1956 sent Lysenkoism into permanent eclipse. The cost of Chinese Lysenkoism was delay in the deployment of orthodox genetics in agriculture rather than destruction of the sort wrought by the parent movement in the USSR.

Loren R. Graham